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*The Introduction of Adaptive Social  
Decision-Making in the Mathematical Modelling  
of Egress Behaviour  
(Volume I)*

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### **DEDICATION**

**This dissertation is dedicated to the memory of Dean Jones, who saw straight through me, got me into trouble and kept me sane. *"You're getting on my nerves."***

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**NOMENCLATURE**

Below is a list of commonly used terms and their description.

<b>Symbol</b>	<b>Meaning</b>
$\  \ _2$	Euclidean Norm
$[x, y]$	Positional Vector
$\sum$	Summation Of Indicated Terms
$\rho$	Density
$\varepsilon$	Random Variable
/m	Per Metre
$A_i$	Exit Attractiveness
$A_{max}$	Maximum Exit Attractiveness
CoHb	Carboxyhaemoglobin
CWT	Cumulative Wait Time (seconds)*
d	Distance (m)
$D_i$	Occupant Motivation *
$D_{max}$	Maximum Occupant Motivation *
f	Occupant Flow (p/m/s)
FED	Fractional Effective Dose
FIC	Fractional Irritant Concentration
$FIC_{HBr}$	Fractional Irritant Concentration For Hydrogen Bromide
$FIC_{HCl}$	Fractional Irritant Concentration For Hydrogen Chloride
$FIC_{HF}$	Fractional Irritant Concentration For Hydrogen Fluoride
$FIC_{NO2}$	Fractional Irritant Concentration For Nitrogen Dioxide
FICO	Fractional Incapacitation Dose For Carbon Monoxide
$FIC_{Org}$	Fractional Irritant Concentration For Organic Gases
$FIC_{SO2}$	Fractional Irritant Concentration For Sodium Dioxide
FIHCN	Fractional Incapacitation Dose For Hydrogen Cyanide
FIN	Fractional Incapacitation Dose For Nitrogen
FIO	Fractional Incapacitation Dose For Reduced Levels Of Oxygen
ft <sup>2</sup> /per	Feet Squared Per Person
K	Extinction Coefficient (/m)
kW/m <sup>2</sup>	Kilowatts Per Metre Squared
m	Metres
m/s	Metres Per Second
m <sup>2</sup> /m <sup>2</sup>	Metre Squared Per Metre Squared
m <sup>2</sup> /per	Metre Squared Per Person
max()	Function Determining Maximum Value For Indicated List Of Variables
mg/l	Milligrams Per Litre

min	Minutes
min ()	Function Determining Minimum Value For Indicated List Of Variables
$n_i$	Nodal Connectivity
$n_{max}$	Maximum Nodal Connectivity
OD	Optical Density
per/ft/min	Persons Per Foot Per Minute
per/m/sec	Persons Per Metre Per Second
PET	Personal Elapsed Time (seconds)*
ppm	Parts Per Million
$Q_i$	Exit Quality *
$S_i$	Occupant Seniority *
$S_{max}$	Maximum Occupant Seniority *
t	Time (seconds, unless otherwise stated)
$t_{conv}$	Time To Incapacitation Due To Convective Heat (seconds)
TET	Total Evacuation Time *
$t_{rad}$	Time To Incapacitation Due To Radiative Heat (seconds)
v	Velocity (m/s)
$VCO_2$	Multiplicative Factor Which Measures Increased Uptake Of CO And HCN Due To $CO_2$ Induced Hyperventilation
$W_a$	Actual Width (m)
$W_e$	Effective Width (m)
$x'$	Derived Value

\* term used in either release or prototype version of buildingEXODUS

## **ABSTRACT**

This dissertation represents an attempt at increasing the behavioural sophistication of evacuation simulations, through the study of evacuation modelling, the development of new behavioural algorithms, their implementation within an existing evacuation model and the testing of the resulting model. This aim is achieved through a number of steps.

Firstly, the range of human behaviour that are exhibited by occupants during the evacuation process is studied. Next, the sophistication of the available evacuation models is investigated and a suitable model is selected and thoroughly assessed (the buildingEXODUS evacuation model). The selected model is then used as a test bed in which to implement the advanced behavioural developments.

The detailed behavioural analysis was conducted to provide the necessary framework, around which an eventual model might be formulated and implemented. This involved the examination of the factors that might influence the occupant's behaviour, the occupant's decision-making process and the eventual occupant behaviour.

The mechanisms implemented within the evacuation models presently available were then investigated to determine the current effectiveness of evacuation modelling. This investigation generated possible ideas as to how the modelling process may be conducted and the possible limitations that would be inherent in this process. Rather than creating a completely new behavioural shell, during which time a significant amount of resources would have been diverted into software engineering, an existing behavioural shell was sought after. The buildingEXODUS model was selected as a shell within which the proposed behavioural developments could be analysed for both practical and technical reasons.

The selected model was then validated against a number of experimental and real-life validation cases. This highlighted a variety of limitations and enabled the detailed workings of the selected model to become familiar. In this process, the sophistication and limitation of this shell (the current buildingEXODUS evacuation model) was established. This was required to properly examine the extent of the proposed behavioural development over the existing model.

Once these limitations were established, the proposed developments then had a realistic basis for comparison. The new behavioural features were made in response to sociological, psychological and physical limitations that had been identified in the existing evacuation models. These developments included a more detailed representation of

- The occupant's familiarity with the enclosure,
- A representation of the occupant's motivation based on the occupant's perception of the surrounding conditions,
- Occupant communication,
- Collective behaviour
- And the ability of the occupant to adapt according to the information available.

These proposed behavioural actions and influential factors were then implemented into the buildingEXODUS model. These features were then examined to determine their satisfactory integration into the overall buildingEXODUS model and their impact upon the sensitivity of the model through the use of hypothetical and actual data-sets.

Each of the new behavioural features provided new occupant capabilities and affected the outcome of the buildingEXODUS simulations. The differences may have been centred on qualitative and/or quantitative aspects of the evacuation, depending on the proposed behaviour in question. However, all of the behavioural features examined produced notable results that enhanced the performance of the model in some manner.

Overall the behavioural developments were seen to increase the flexibility and functionality of the model without compromising the previously established ability of the model to cope with the fundamentals of human behaviour. These improvements were therefore seen to further advance the capability of the model to accurately determine the safety of an enclosure during an evacuation through a better understanding of the occupant response and a better and more thorough representation of human behaviour.

"... I do indeed believe that there is a certain contrast between, say, people in scientific professions and people working in the arts. Often there is even mutual suspicion and irritation, and in some cases one group greatly undervalues the other. Fortunately there is no one who actually has only feeling or only thinking properties. They intermingle like the colours of the rainbow and cannot be sharply divided. Perhaps there is even a transitional group, like the green between the yellow and the blue of the rainbow. This transitional group does not have a particular preference for thinking or feeling, but believes that one cannot do without the one or the other. At any rate, it is unprejudiced enough to wish for a better understanding between the two parties."

M.C.Escher:

CHAPTER 1 INTRODUCTION

People are killed in fires with an alarming regularity. If we examine the figures for the UK alone, although a gradual decline is evident (see Figure 1-1), the number of deaths due to fire have consistently fallen between 600 and 950 per annum in the past decade. The majority of these are in small-scale dwelling fires. Fire related deaths become more prominent and newsworthy when large-scale high-profile fires occur. These have included fires that occurred in the UK (such as those at the Manchester Woolworth's, Kings Cross Underground station, the Summerland complex and the Valley Parade Football Ground) and those that occurred abroad (including incidents at the Stardust Disco (Dublin), MGM Grand Hotel (Las Vegas), the DuPont Plaza, the Beverly Hills Supper Club, Dusseldorf Airport and the more recent tragedy at the Gothenburg Disco) [1,2]. All of these incidents exemplify the destructive potential of fire. This is despite the introduction of numerous and expensive technological developments (see Chapter 2 and Chapter 9)[1]. As modern safety mechanisms are produced, increasing the level of fire safety within an enclosure, architects supersede these developments through designing more complex structures. The unforeseen hazards produced by these new enclosures limit the potential benefit produced through the advances in fire safety science.

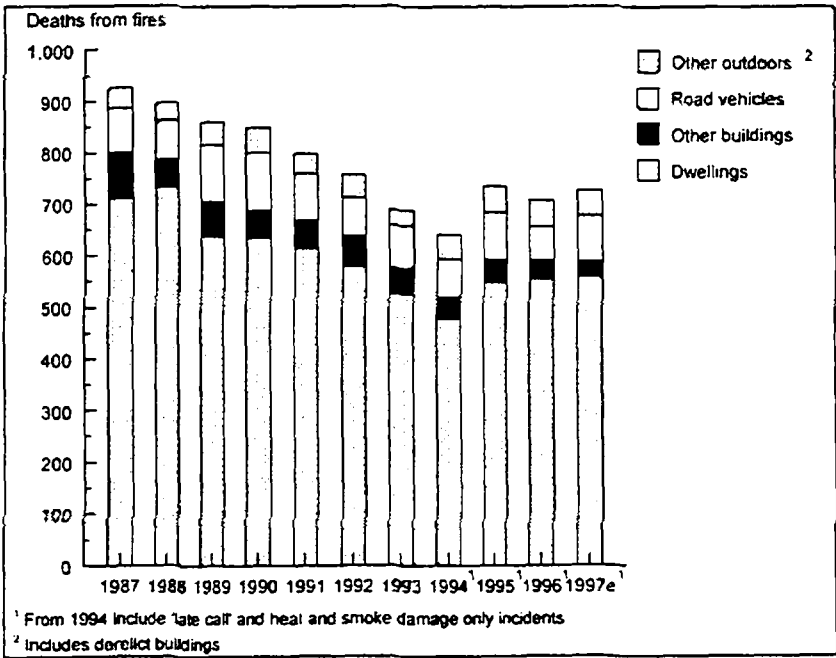


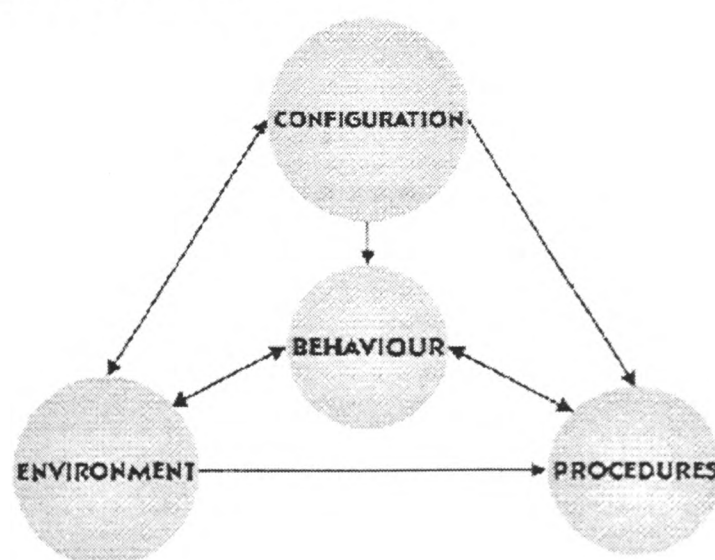
FIGURE 1-1: DEATH BY FIRES IN THE UK 1987-1997[3]

The provisions to improve fire safety tend to be made on the assumption that the operatives involved in an emergency will be *capable, informed* and *willing* to utilise the technology provided in a manner that facilitates safe egress. Unfortunately the history

(both past and recent) of fire tragedies point to the contrary [1,3]; that founding the provision of safe egress on the assumption that the occupants and staff involved react in an optimal and uniform fashion dangerously eliminates a significant variable from the egress calculation. This need not be due to an inability on behalf of the occupants to perform complex tasks but may be due to an occupant not responding to an alarm system as predicted or not perceiving the placement of a signage system (see Chapter 2)[1]. It is asserted that this form of sub-optimal behaviour is *inevitable* during any evacuation and reduces the efficiency of the evacuation. *However, this impact can be minimised if it is recognised and accommodated.*

Until recently many of the safety developments introduced to augment the evacuation process arrived from a particular school of thought; namely from an entirely physical perspective, excluding the influence of human behaviour upon the outcome of an evacuation, in the face of a wealth of contrary evidence [1,4]. With the increasing variability and complexity of structures, a method is required to accurately identify the potential risks to the occupant population, where these risks reside and how best to control and manage them. For this to be the case, it would require the representation of *all* aspects of the evacuation, rather than subjectively elevating the influence of one area at the expense of others. This work is an attempt to produce a modelling solution to this problem of fire safety, through the development of a flexible simulation model that incorporates a wide range of influences, including those of the evacuating population.

In order to assess fully the potential evacuation efficiency of an enclosure, it is essential to address the *configurational*, *environmental*, *behavioural* and *procedural* aspects of the evacuation process (see Figure 1-2).



**FIGURE 1-2: THE FOUR MAIN INTERACTING ASPECTS TO BE CONSIDERED IN THE OPTIMAL DESIGN OF AN ENCLOSURE FOR EVACUATION [5,6].**



*Configurational* considerations are those generally covered by traditional building codes and involve building layout, number of exits, exit width, travel distance etc. In the event of fire, *environmental* aspects need to be considered. These include the likely debilitating effects on the building occupants of heat, toxic and irritant gases and the impact of increasing smoke density on travel speeds and way-finding capabilities. *Procedural* aspects cover the actions of staff, level of occupant evacuation training, occupant prior knowledge of the enclosure, emergency signage etc. Finally, and possibly most importantly, the likely *behavioural responses* of the occupants must be considered. These include aspects such as the occupants' initial response to the call to evacuate, likely travel speeds, family/group interactions etc.

As architects continue to implement novel concepts in building design, they are increasingly faced with the dilemma of *demonstrating* that their concepts are safe and that the occupants will be able to efficiently evacuate in the event of an emergency. *How then do we best guarantee occupant safety, given that an evacuation is required from a particular enclosure?* Traditionally, two techniques have been used to meet these needs: *full-scale evacuation* demonstration and the adherence to *prescriptive building codes*.

A full-scale evacuation demonstration involves staging an evacuation exercise using a representative target population within the structure. Such an approach poses considerable ethical, practical and financial problems that bring into question its viability (see Chapter 2)[1].

The ethical problems concern the threat of injury to the participants and the lack of realism inherent in any demonstration evacuation scenario. As volunteers cannot be subjected to mental trauma or to the physical ramifications of a real emergency situation such as smoke, fire and debris, such an exercise provides little useful information regarding the suitability of the design in the event of a real emergency [1].

On a practical level, when evacuation drills are performed, usually only a single evacuation trial is undertaken. Thus there can be limited confidence that the test - whether successful or not - truly represents the evacuation capability of the structure. From a design point of view, a single test does not provide sufficient information to arrange the lay out of the structure for optimal evacuation efficiency [7].

The need to perform repeated experiments should come as no surprise as even under the most controlled experimental conditions, no evacuation exercise involving crowds of real people will produce identical results if the exercise is repeated - even if the same people are used. For any structure/population/environment combination, the evacuation performance of the combination is likely to follow some form of distribution.

Finally, to perform even a single full-scale evacuation demonstration can be expensive, if many such experiments need to be performed then the task can become prohibitively expensive. Furthermore, the evacuation demonstration is usually performed *after* the structure has been constructed. Any design alterations that may be required will thus prove extremely expensive to implement [1,8].

It should be remembered that such experiments are an attempt to *model* the events of an actual emergency. Critics of the modelling approach to understanding evacuation behaviour often point to the advantages of conducting a real-life evacuation. This advantage is based around the use of actual participants. The fact that volunteer occupants are used does not, however, *necessarily* produce realistic results or increase the confidence in the quality of the results. The conditions produced are in effect a *simulation* of the expected events, with control exerted by the experimenters over the potential risks involved, the target population used and often the levels of information available to the participants (indeed, the experimenters are legally and morally bound to maintain this control) [9-11]. *The fact that the situation is contrived detracts from the reliability of the results produced.* This is often overlooked by those viewing the results produced, due to the perceived trustworthiness of experimental data.

Thus experimental means of assessing building design in a routine manner is far from ideal. An alternative to evacuation demonstrations is simply to adhere to the existing prescriptive building codes. Prescriptive building codes set out to accept/reject a proposed design on the basis of its adherence to a set of rigid regulations set down in the code [12]. These tend to relate entirely to the physical aspects of the evacuation process, to the exclusion of all other influences. Generally, this method fails to address all of the issues that affect the outcome of an evacuation in an analytical manner, preferring to rely almost totally on judgement and a set of prescriptive rules. As these prescriptive rules have an almost total reliance on configurational considerations such as travel-distance

and exit width they can prove to be too restrictive and insensitive to the changing conditions that may arise during the lifetime of a building and during an evacuation. Given the lack of rigorous analysis of the prescriptive codes and the variety of codes available, it may also be possible to produce which satisfy a specific set of codes but is not necessarily safe. Furthermore, as these traditional prescriptive methods are insensitive to human behaviour or likely fire scenarios, it is unclear if they indeed offer the optimal solution in terms of evacuation efficiency.

As with the conduction of evacuation trials, the application of prescriptive codes is a simplistic attempt at modelling and predicting the '*egressibility*' [13] of the enclosure. It is based on the assumption that the configuration is the dominant influence during an evacuation, to the extent that all other considerations are negligible in comparison. A vast amount of research now exists to refute this assumption (see Chapter 2) [1], therefore undermining the future use of *prescriptive* codes based simply on configurational aspect.

A third approach to assessing the level of safety attained in a building is that of *evacuation simulation*. Computer based evacuation models [14-48] offer the potential of overcoming the shortfalls outlined and address the needs not only of the designers but also the legislators and users in the emerging era of prescriptive based codes (where the safety of a building is determined through analysing its ability to be evacuated safely according to local conditions). However, they are often inappropriately seen as a *panacea* to the problems of fire safety, providing an ideal solution. This is obviously not the case and this misinterpretation of the modelling potential, often maintained by modellers themselves, constantly leads to disappointment and provides an impediment to the more widespread use of this mechanism. This shortfall in the performance of evacuation models thus far, identifies the need to produce more realistic goals and increase the quality of the models themselves. *Hence, the purpose of this dissertation is the study of evacuation modelling.*

The evacuation models presently available *do not* adequately represent all aspects of occupant behaviour (see Chapter 3) [1,8]. This limits their usefulness to engineers and, more importantly, potentially reduces the safety of the constructions to which they are applied. As described in Chapter 3, the models that are currently available cope with

various aspects of occupant behaviour. Numerous models represent the importance of *some* aspects of the evacuation process, such as the impact of the enclosure configuration upon the passage of the population [8]. However, *none of the models currently available include a comprehensive representation of the occupant decision-making process that treats all facets of occupant behaviour in equal detail.* This obviously generates numerous problems.

It is therefore necessary to ascertain a detailed understanding of the current position of evacuation modelling and its potential for development, so as to understand the areas most ripe for improvement. Namely

- What behaviours are included in the evacuation models currently available?
- Given that these behavioural actions are included, is the representation adequate to describe the potential complexity and range of behaviour expected during actual evacuations?
- Finally, if the behavioural measures simulated are not adequate, can they be developed and included within evacuation models and will their inclusion result in an improved representation of reality?

The response to these key questions forms the basis of this dissertation. Implicit in this response is an understanding of the factors that require modelling; that is those behaviours that are deemed to be significant during an evacuation. This requires a detailed analysis of evacuation behaviour, incorporating a multi-disciplinary understanding of influential factors.

*This dissertation is therefore an attempt at advancing the technology used to simulate the occupant response to an evacuation. This will involve the development of a number of algorithms reflecting the occupant decision-making process and an enriching of the factors generally used to simulate evacuations.* As a starting point for this development, an advanced evacuation model will be adopted as the baseline model. This will enable the evacuation model to more realistically simulate occupant behaviour and therefore better predict the safety levels and potential dangers of an enclosure. It is not claimed that the algorithms represent all expected occupant behaviour. However, the concepts demonstrated should advance the evacuation model chosen towards a more flexible and sensitive representation of egress behaviour.

These developments will be demonstrated using the buildingEXODUS evacuation model [5-7,21-28]. This model has been selected for practical and technical reasons. The practical reasons concern the readily available and well-documented source code [23], while the technical reasons relate to the well-structured and engineered nature of the source code allowing easy adaptation[5-7,21-22,24-28].

Unlike most of the evacuation models currently available, the planned developments are not centred around purely physical factors or upon global considerations imposed upon entire populations [8], but instead focus on the individual, his knowledge, experiences and social interactions and the bearing that these factors have on the evolving evacuation. In particular, this work is concerned with modelling the answers to the following questions:

- *What facets of the occupant affect the egress behaviour exhibited?* How do the experiences and personal traits of the occupant influence his behaviour during the evacuation? Does the occupant's identity and his membership of specific social groupings have an impact upon his behaviour?
- *How do the occupant's attributes develop during the evacuation, through their interaction with unfolding events?* How does the occupant's motivation and perception of events change during an evacuation and how does this impact upon their behaviour?
- *What influences will the occupant be subject to that may influence their behaviour?* Will the occupant pass through smoke? How will the occupant react to occupant congestion?
- *What analytical tools will be available to the occupant that may be used in calculating potential egress routes?* Can the occupant analyse the consequences of potential decisions? Are they able to receive visual information on which to base these calculations?
- *What means are available to the occupant to receive and transmit information during an evacuation?* What is the nature of this information (e.g. the existence of an emergency, potential new routes, etc). How will the occupants' identity impact upon the perception of this information?
- *Given all of the previous factors, what decisions are eventually made by the occupant?*

The process of answering these questions, as well as numerous others, will go some way to providing a more comprehensive behavioural model. However, the *nature* of the solution also affects the success and accuracy of the solution. It is vital to the success of this project that where behavioural activities occur, that their influences, processes and outcomes are represented at an *individual* level rather than at a global or cumulative level, as in the case of the majority of existing models (see Chapter 3). Not only does this

individual representation allow the occupants a more localised view of the evacuation, but also more accurately represents the location and distribution of information throughout the population, with all of the subsequent behavioural differences that this may cause.

In simple terms, the occupant is assumed to arrive at the evacuation with life experience and attributes that will influence his ability to evacuate and the decisions he makes in achieving this goal. During the evacuation the occupant will interact with a number of external factors (be they environmental, social, physical, etc.) that will impact upon his attributes. The occupant may anticipate this impact and the results of this analysis may be transferred to other interested parties. This process leads the occupant to decisions that will govern his actions during the evacuation. This is the decision-making blueprint upon which this dissertation is based.

These decisions will not be based around a single aspect of the occupant's experience (such as the physical experience or the psychological experience). Instead, these decisions involve those influences that are appropriate at the time that the occupant is sensitive to them, be they *physical*, *psychological* or *sociological*.

For this to be achieved a number of problems have to be addressed in the field of evacuation modelling. It is not asserted that these problems will be addressed for the first time. However, the current absence of a comprehensive behavioural model that is subject to scrutiny and which has been verified through testing, suggests that the problem has until now only been partially addressed. It is also not suggested that all of the problems will be resolved with this dissertation. Instead through detailed analysis the problems can be initially addressed, thus highlighting the areas in which future development are vital.

Modelling is often seen as a *black art* by those not involved in the process. It is viewed with suspicion by those outside of the field and dismissed by its detractors as liable to misuse, through the ability of the modellers to *engineer results* rather than producing an *engineering solution*. This is a credible criticism, although one that can equally be levelled at any area of research. This dissertation through its rigour and candour is an initial attempt at researching, designing, implementing and verifying an evacuation model in as transparent a manner as possible, to overcome such detractions.

*Modelling is a complex process*, as it requires an understanding of two generally unrelated subject areas: the area that is to be modelled and the method used to produce the model. Evacuation modelling is an emerging field of study. As such it is constantly being redefined, with the boundaries within which it operates expanding and contracting accordingly. During this dissertation the modelling process itself will be analysed in some detail prior to the proposed development and testing of new behavioural representations, to gain a detailed understanding of the problems facing the modeller.

The difficulty of the process is compounded by the complex nature of the problem being studied. The exclusion of one or more of the influential factors only confirms the worst fears of a sceptical examiner (see Figure 1-2); that the model has been designed to side-step difficult issues or to guarantee particular outcomes. The extensive nature of this dissertation, especially in its analysis of expected occupant behaviour, is an attempt at initiating the task of comprehensively modelling evacuation behaviour.

*This work is concerned with the development of an evacuation model that is capable of representing a wide scope of occupant behaviour.* For this to be the case, it is necessary to establish an understanding of typical evacuation behaviour and the causal factors behind such behaviour that would form a basis upon which a behavioural model might be based. This behaviour should be derived from actual events and should not simply occur through random processes. To represent egress behaviour realistically, simulated actions should be based upon similar causal factors as those evident in real-life. This would enable the model to be *predictive*, as by representing the behaviour as being based on perception, cognition and performance, an evacuation could be generated through the imposition of initial conditions. The simulation would then proceed, with the causal factors being examined to determine the occupant activities.

Given the incomplete nature of the majority of data-sets available, it would be unrealistic to assume that individual occupant behaviour could be replicated *exactly*. However, given a relatively detailed data set representing an actual incident (such as the Beverly Hills Supper Club incident [1,49-52] or the Summerland incident [1,53-54]), it should be possible to develop behavioural models that are capable of producing representative

behavioural responses, allowing the production of an acceptable distribution of expected behavioural responses and subsequent outcomes.

*Models must be used and verified.* The development of an evacuation model should be based upon *empirical foundations* [1]. These foundations must be verified to determine their strength through use and through comparison with relevant data. A purely theoretical model is an idea awaiting implementation. Even though a model may have been produced in line with empirical methods, without its full implementation, the empirical process will have been interrupted. Without this implementation, a behavioural model is not subject to the rigorous testing required for acceptance in other areas of modelling and would be open to criticism. Indeed the very process of implementation requires a significant degree of component, functional and compatibility testing that can only enhance the structure of the model itself and enhance the integrity of the model [7]. The process of implementation requires an additional understanding of the shell (computational in this case) used to couch the behavioural model, the interaction between the two entities and an analysis of the results produced.

Several forms of verification are vital to the development of a model: namely component testing and integration analysis [7]. It is conceivable (as in this case) that the computational shell may arrive already having some of these procedures completed. The implementation of the behavioural model must be proved to interact reliably with the existing model components. It is only at this point that the resultant behaviour can be examined. This should be tested for qualitative and quantitative accuracy against as many data sources as possible.

*Modelling is therefore dependent upon data* for the design and verification process. Evacuation modelling has, until the latter part of the twentieth century, been starved of this data. By its nature, data concerning fire events are a sensitive and difficult resource to collect. The collection and analysis of this data have also tended not to come from a modelling point of view and will have therefore not been subject to the forensic rigour required for use in the modelling process.

The acquisition of data against which the model can be compared is a significant task in itself. It may arrive from a variety of sources (fire investigation, related fields of study,



hypothetical situations, etc.) some of which will be more reliable and detailed than others. As long as this data is accompanied by a relevant analysis of its reliability and its scope, then most sources may provide some comparative benefit.

*This work attempts to follow as empirical a methodology as possible, deriving data from as many sources as are available.* Where actual data is not available hypothetical scenarios have been included. This is to investigate the relevance and acceptability of the *concept* as much as the quantitative results produced.

This dissertation is an attempt at resolving and instigating a number of processes. It is structured in as logical and self-contained a manner as possible. This is partly due to the size of the task and to delineate the areas of analysis more clearly. The tasks attempted are to:

***Present and analyse the range of human behaviour thought to be relevant to evacuation so that an initial framework can be generated suggesting areas of development.*** In Chapter 2, the factors that are expected to impact upon occupant behaviour and the occupant's behavioural response to them are examined. The purpose of this is to develop a concept of the form of occupant behaviour that is anticipated during an evacuation and also the conditions under which they occur. This is vital in enabling us to model evacuation behaviour. This process will allow the production of a behavioural model that includes those factors that influence occupant behaviour as well as the expected behavioural response. This is not a simple literature review but, through the detail of its analysis, allows the production of a comprehensive model, which acts as a framework for the proposed developments.

***Examine the current state of evacuation modelling through investigating those models available, the assumptions on which they are based and the results obtained through their use.*** An investigation into the scope of evacuation modelling as it currently stands is then presented. This is essential to acquire an understanding of the tools used to represent the evacuation process and to assess areas of potential advancement. This is limited to that work which has been scrutinised by experts in the field. Therefore in Chapter 3, models are examined on the basis of the relevant literature currently available. Although the quality of the scrutiny may vary through only examining this form of information, a certain level of authenticity and transparency is guaranteed. This

investigation includes the buildingEXODUS model, which is used as a shell to examine and display the proposed behaviour throughout. The models are categorised according to the mechanisms used to represent occupant behaviour. This will provide us with a benchmark against which the proposed developments can be measured as well as suggesting the potential limitations of the methods examined.

***Develop an expertise with the chosen computational shell through its use and through a process of validation.*** For the behavioural model to be implemented and used, a computational shell is required. It would have been possible to create an entirely new evacuation model. However, seeing as a number of competent physical models already exist [8], it was seen as counter-productive to ‘reinvent the wheel’. In Chapter 4 the buildingEXODUS model is further examined, implementing a number of validation cases. This is to demonstrate the present sophistication of the model, to highlight potential weaknesses that may arise and to establish a level of expertise with the model. If the model is to be used as an arena for behavioural development and analysis, then we must be aware of the important behaviours that are not included within the model, so as to either compensate for their absence or to account for them in any results generated.

***Develop, implement and verify a number of proposed behaviours within the computational shell, drawn directly from the analysis of the subject matter.*** In Chapter 5-8 the proposed behavioural features are outlined. In Chapter 5, developments concerning internal occupant attributes and simplistic occupant capabilities are outlined, enhancing the social representation of the occupant. In Chapter 6, the interaction of the occupant with a number of external features is examined, including their spatial interaction with the geometry, other members of the population and the ability of occupants to have their passage delayed by procedural requirements, geographical necessity or social obstructions. In Chapter 7, the occupant’s dynamic response to the external conditions is examined, crediting the occupant with experiential processes that are not simply based on stimulus-response actions. These include a more sophisticated occupant interaction with a deteriorating environment, the dynamic nature of occupant motivation and the localised representation of potential egress routes. Finally, in Chapter 8, the occupant is seen as a decision-making engine that organises and engineers his responses to the environmental conditions according to analysis and estimation, as well

as to the provision of new information. This is based on communication, adaptation (to both the environment and to the surrounding population) and social cohesion.

The general principles on which these behavioural developments are based are outlined in Chapter 2. However, the specific details and evidence for these behavioural processes are addressed in relation to the proposed behaviours in more detail. These behavioural expectations are compared against the results produced by the present buildingEXODUS model, to determine the extent and accuracy of the present behavioural representation. Finally, the proposed model is outlined in detail, including flow charts and any relevant mathematical formulae. A number of verification cases will be described, each of which will have been designed specifically to interrogate the proposed behaviour accordingly. The results produced will be used to flag the advances of the proposed developments. The models are verified through comparison with experimental data and the use of hypothetical data-sets.

***Examine the interaction between the proposed models.*** In Chapter 9, the proposed developments are combined in an attempt to simulate an actual evacuation. The Beverly Hills Supper Club incident of 1977 was a tragic event in which 165 people were killed [1]. Due to the scale of the incident and the availability of data concerning the evacuee behaviour (although still incomplete), it provides a means by which to simultaneously examine the flexibility and functionality of the proposed developments. This is not claimed to be a detailed validation of the proposed behavioural developments. Rather, it is provided to demonstrate that the proposed algorithms are able to work in unison thereby increasing the flexibility and functionality of the evacuation model.

***Initiate the design and creation of an integrated behavioural model.*** In Chapter 10, the work is drawn together with some concluding remarks, describing findings of the work and any possible advantages produced through its implementation. Finally, a unified approach is developed describing a complete behavioural model. This will be developed in such a way as to suggest the implementation within the buildingEXODUS model as future work. Effectively this model is the culmination of the dissertation, drawing together the behavioural analysis with the complete integration of the proposed behaviour outlined in Chapters 5-8.

*The goal of this dissertation is to extend the behavioural sophistication of evacuation modelling through the development of a particular evacuation model, namely buildingEXODUS, incorporating an increased number of observed occupant behaviours.* This is achieved on the assumption that evacuation modelling is the most appropriate means by which the safety of enclosures can be ascertained. The benefits of the concepts examined are not limited to the buildingEXODUS model, but would benefit any model that is able to address the problems highlighted and at present do not include reference to specific forms of occupant behaviour.

Without an increased level of safety awareness, the inherent risk that is latent within all structures cannot be fully determined, preventing the necessary procedural and configurational alterations required to combat these dangers. This will therefore diminish the preparedness of the safety staff at hand to resolve any potential difficulties and consequently place the occupants of the structure at greater risk. As such, this dissertation is an attempt to provide a useful engineering tool that may be utilised in the reduction of potential risks, rather than as a purely academic exercise.

## CHAPTER 2 THE ANALYSIS OF EXPECTED OCCUPANT BEHAVIOUR: ESCAPE AS A SOCIAL RESPONSE

*“By the mere fact that he forms part of an organised crowd, man descends several rungs in the ladder of civilisation. Isolated, he may be a cultivated individual; in a crowd, he is a barbarian—that is, a creature acting on instinct.”[74]*

Prior to the development of an evacuation model, it is vital to familiarise oneself with the fundamental subject matter being modelled; namely the occupant and their transformation into an evacuee. Without a detailed understanding of the occupant and the occupant response, one would be addressing the outcome of an evacuation without comprehending the most significant variable in the evacuation ‘equation’. In this chapter, a rigorous analysis takes place concerning the occupant behaviour to provide a better understanding and therefore assist in the process of simulation. For further details, the reader is referred to the Society of Fire Protection Engineering Report that is based on this chapter [1].

*It would be unrealistic to assume that individual occupant behaviour could be consistently simulated to a high degree of accuracy even after the extensive development of an evacuation model.* Therefore the exact replication of specific evacuation events should not be expected, as they represent a unique example of what is expected to happen during an evacuation. However, it should be possible to develop behavioural models that are capable of producing a distribution of representative behavioural responses, forming an expectation of the probable outcome, given a set of initial conditions. Therefore, given that the original data-set exists and is relatively complete, then the behavioural activities seen in the actual example should fall within the distribution of simulated behaviour produced by the evacuation model.

For this to be the case, it is necessary to establish an understanding of typical evacuation behaviour and the causal factors behind such behaviour. This can then form a foundation upon which a flexible and comprehensive behavioural model might be based.

This chapter then examines the occupant behaviour exhibited during evacuation conditions, the decision process through which the occupant passes to arrive at these behavioural actions and the factors that influence these decisions. This analysis is based on a review of a wide range of published literature concerning evacuation behaviour.

Factors influencing evacuation performance can be categorised into four broad areas namely, *configurational*, *environmental*, *procedural* and most importantly, *behavioural*. Specific factors in each of these categories include the function of the enclosure, the type of alarm system provided within the structure, the physical make-up of the population, occupant familiarity with the enclosure, the presence/absence of smoke, heat and toxic gases, as well as numerous other considerations. The contributory factors associated with each of the four influencing categories are examined in detail.

For the evacuation model to function appropriately, it should accurately represent the processes involved during the evacuation from all of the four areas outlined. This representation should not be based *solely* upon the final occupant actions, but should instead be reliant upon constituent influential factors that affect the occupant's decision-making process.

This chapter initially addresses what was until recently perceived as being the most common and most influential evacuation behaviour, *panic*. This belief was propagated by the media and maintained by the emerging field of evacuation modelling, as it supported the physical models of the time. Through investigation, panic behaviour is now moved from being classified as a commonplace behavioural *action* to a rare although still influential behavioural *factor*.

Once this has been examined, the other factors that influence occupant behaviour are listed and briefly detailed. The expected occupant response to these factors is then detailed, providing a comprehensive understanding of potential evacuee actions. This analysis of the causal factors and the resulting occupant behaviour is vital in our attempt at developing an accurate behavioural model. As already highlighted, it is not enough to produce models that generate accurate results purely by statistical (i.e. random-based) processes. Although the results produced may *generally* be accurate, the lack of contextual influence may cause the model to be insensitive to important causal factors and would have difficulty representing unusual or unexpected events. This therefore precludes qualitative analysis to a large degree, a vital component in understanding occupant behaviour.

Finally, all of these factors are brought together to produce a general behavioural model (see Figure 2-1). This will summarise the most significant factors, processes and actions identified in the prior discussions. Although this basic model will require significant development, it will form the basis for further analysis and progress later in this dissertation. The contents of this model will signal some of the expectations that the proposed behavioural developments will have to meet.

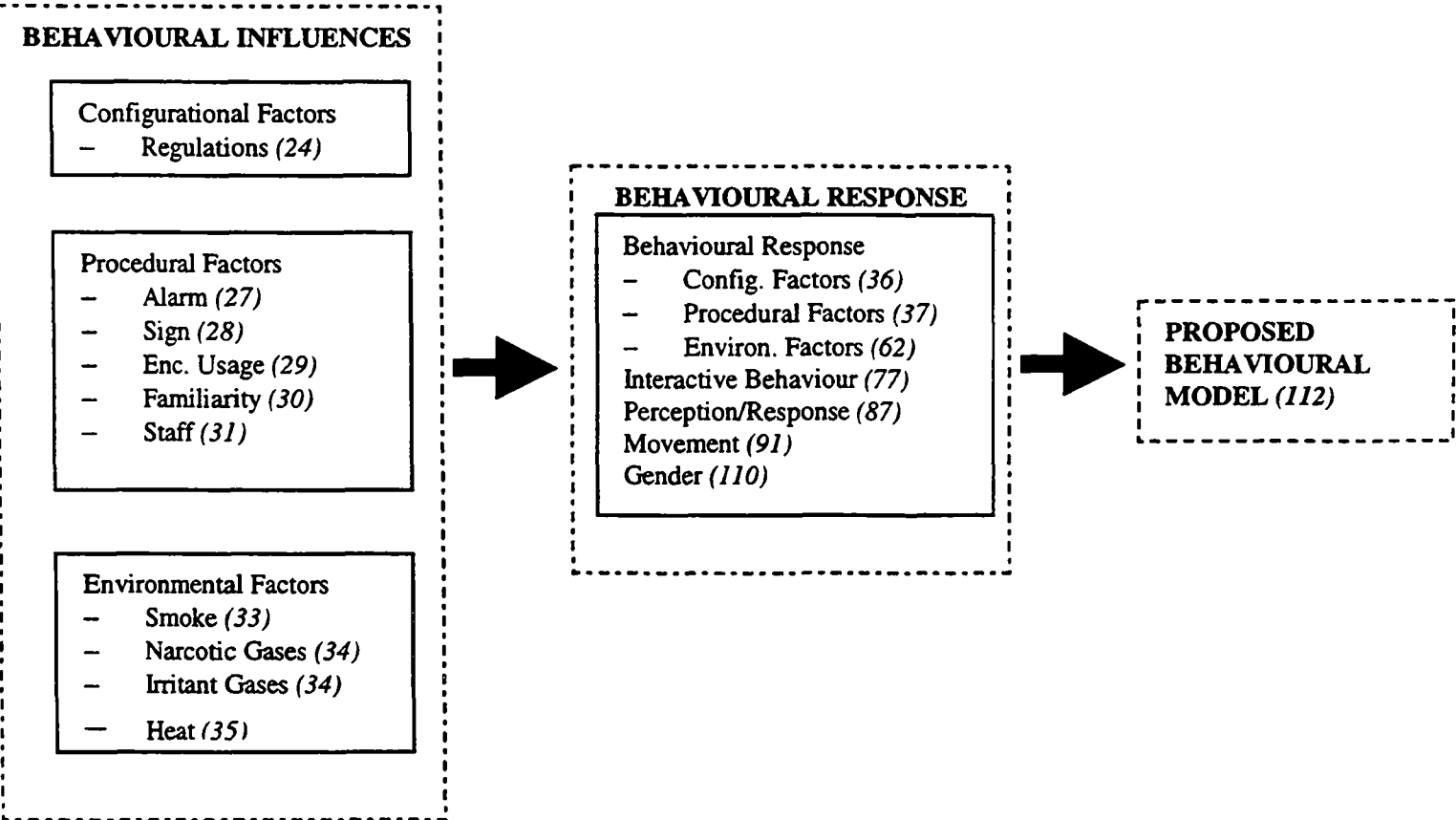


FIGURE 2-1: STRUCTURE OF CHAPTER 2.

The purpose of this discussion is then not to exhaustively represent each of the topics identified, as each of them warrant extensive investigations in their own right. Instead, the purpose of this chapter is to highlight the areas that would need to be addressed in the development of behavioural models and describe the expected factors and responses.

## 2.0 OBSERVED BEHAVIOUR DURING EVACUATION

### 2.1 Panic

It had been, for a number of years, the ‘common-sense’ view that under extreme conditions, such as fire evacuations, it was the norm for untrained, inexperienced individuals to ‘panic’, and therefore act in an irrational and possibly self-destructive manner. This is due in part to the perception portrayed by the media in reporting major disasters. As Quarantelli describes,

*“Part of the tenaciousness of the belief that people will not behave well when facing danger is rooted in literary and journalistic accounts of the actions of people in major emergencies.”[55]*

Quarantelli characterises panic behaviour according to the fear of a perceived immediate danger to the occupant’s existence, resulting in individualistic action, that makes no

attempt to address the problem, only to remove the occupant from immediate danger.  
[55]

The assumption that panic behaviour formed a significant proportion of the evacuee response would invalidate much of the work done in the field of modelling human behaviour, as if behaviour were irrational and random, it would not be possible to simulate with any degree of certainty.

Non-adaptive behaviour is now considered to represent only a small proportion of behaviour in fire incidents, even under serious and life-threatening conditions [49-52,56-58]. Even under the most terrible conditions, such as those at the Coconut Grove fire, Quarantelli and Dynes observed that only a very small proportion of the population could be said to have panicked [49-50,59]. Indeed one of the causes for the misinterpretation of 'panic' behaviour was the reliance on *anecdotal evidence*. This tended to imply that panic was commonplace, but as Wood [57] suggested, this is probably the case because when viewed, completely irrational behaviour is liable to be both spectacular and memorable, and that in fact only 5% of behaviour seen in evacuations could be categorised as non-adaptive. In addition, Bryan [60] identified that panic did not occur in isolation, but in *clusters*. In effect, panic was communicated between individuals, causing non-adaptive behaviour to occur in groups, adding to its memorable nature.

Unsuccessful behaviour and behaviour whose motives are not fully understood are often incorrectly labelled as panic. Indeed, reports of panic are now frequently seen more as a *description* of behaviour by a third party, rather than a useful explanation of the behaviour [61,62]. This can be seen clearly from the manner in which the media report serious incidences in comparison to the recollections of those involved. For instance, in the incident at the 1979 Who concert in Ohio a national columnist reported that the crowd,

“ *stomped 11 persons to death [after] having numbed their brains on weeds, chemicals, and Southern Comfort...*” [59]

In actuality, the problems were caused by lack of communication and configuration problems. This type of reporting also occurred in response to the incidents at the Beverly Hills Supper Club and the Hillsborough Football Ground [49-53,63]. In these cases, although it is undeniable that small amounts of non-adaptive behaviour may have



occurred, this occurrence was not a major contributor to the overall loss of life [49-53,63].

When the amount of information available to an individual is compiled, and behaviour is then examined, instead of viewing behaviour in a system wide context, behaviour may not seem quite so irrational [64]. As Canter commented,

*“Behaviour in fires can be understood as a logical attempt to deal with a complex, rapidly changing situation, in which a minimum of information is available.”*[65]

identifying behaviour, in general, as a rational response to a occurrence about which knowledge is at a premium. Such is the nebulous nature of the term ‘panic’, that there exists a number of definitions which might be centred on the effect of the behaviour on the individual [66] or the effect on those around the individual [57-61]. All of this adds to the misinterpretation of the frequency of irrational behaviour.

An example of a common misinterpretation might concern a mother frantically searching for her child. To an ill-informed observer, her movements might indicate a ‘panic’ reaction to the incidence of the fire. This would be the traditional third party definition of panic. However, the woman may be making an intelligent attempt to locate her child, which, in this case, involves covering a large area (which might be interpreted as ‘frantic movement’), and attempting to communicate with her child (which may be seen as ‘frenzied screaming’).

A second scenario may involve the mass movement of occupants towards an exit at high speed. The third party observer may label this as a population ‘*stampeding*’ from the enclosure [59]. The members of this population may have in fact taken a rational decision to evacuate as quickly as possible because they were aware of the speed that the fire was spreading throughout the enclosure [57].

Generally, panic is seen to represent a breakdown in the normal social constraints and civility so that the occupant moves and acts in a mutually destructive manner. Ironically, although the occupant is seen to be acting selfishly, in their disregard for others, the term also requires the occupant to make misjudgements and take inappropriate actions [55]. A more complete definition is provided by Schultz, who views panic as

*“a fear-induced flight behaviour which is non-rational, non-adaptive, and non-social, which serves to reduce the escape possibilities of the group as a whole”*. [67]

Here, instead of ‘barbarians’ [59] occupants are seen as ignoring the normal conventions rather than contravening them. The importance of this definition is that it links panic to an observable trait; that of the breakdown of social norms and roles. This allows the approximation of the occurrence of panic during times of danger, through the examination of group maintenance. In the vast majority of cases, the social structures that were in position prior to the occurrence of an incident, all still in position after the incident has finished [49-52,55,59]. Where this type of behaviour was expected to be prevalent in a tragedy such as the Beverly Hills Supper Club incident, Johnson and Feinberg [49-52] found that the breakdown of social groups due to non-adaptive behaviour was not the norm at all.

Another, more subtle form of panic, initially identified by Carrol [68] is that of inaction, or ‘negative panic’. It is less obvious, as its occurrence is not quite as startling as the other forms of panic, and by definition has no defining or obvious traits. As Muir pointed out,

*“Unlike panic, behavioural inaction has received little attention, yet evidence from disaster situations, seems to indicate that it is a more likely response than that of panic in a high stress situation”[69]*

Allerton [70] confirmed this assertion, identifying that 10-28% of people did little or nothing to escape from danger, indicating ‘negative panic’ as more prevalent than traditional panic.

The identification of panic behaviour is also linked to a number of myths attributed to the behaviour and motives of crowds [71]. These suggest that crowds are irrational, suggestible and are incapable of being managed [72-74]. All of these lead to the conclusion that crowd activities are panic-based. In reality, as will be demonstrated in the proceeding chapters, crowd activities are made up of individual occupant behaviour. This behaviour is based upon their position in a role structure and the information available to them, which makes the influence of external forces (authority figures, for instance) dependent upon the social filter provided by this role.

The importance of identifying panic as a relatively rare behaviour is apparent, as it justifies a more diverse behavioural model, which would have to deal with more than instinctive, irrational or even random actions. This model would require intelligent

occupant making decisions based upon the events around them. That is not to say that this form of behaviour should be entirely neglected as it can have a significant effect upon the outcome of an evacuation, especially if it occurs at inopportune locations, resulting in the blockage of a busy passageway, for instance. Recent developments in the approach to the ‘panic model’ was summarised by Sime in his examination of occupant behaviour in domestic emergencies. In response to his findings he commented that,

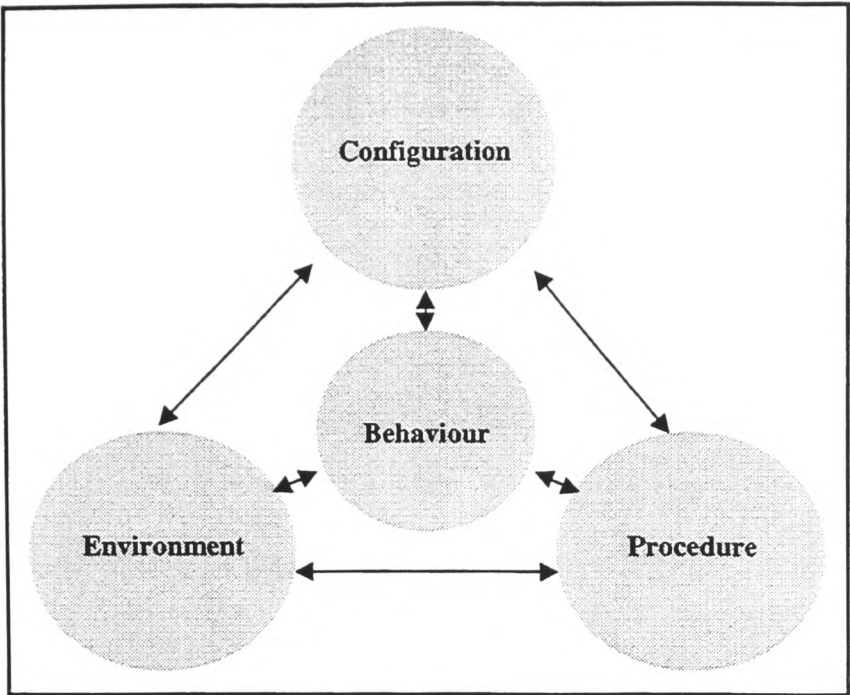
*“The panic scenario of escape behaviour appears far less consistent with the results of the analysis, than a model which takes into account the limited information available to people in the early stage of the fire, the interactions between the people present and the role related behaviour” [54]*

## 2.2 FACTORS INFLUENCING EVACUATION

A number of factors are known to influence evacuation efficiency. These can be collected into four broad categories, these are:

- The *Configuration* of the Enclosure. Encompassing the effects on behaviour of the geography of the structure, including exit widths, arrangement of exits, etc.
- The *Procedures* implemented within the Enclosure. This would entail the configuration knowledge of the occupants, the training and activities of staff, and the familiarity of individual occupants with the exit availability.
- The *Environment* inside the Structure. This describes the effects of heat, toxins, and smoke on the occupant’s ability to navigate and make decisions. The nature and location of debris may also be a factor.
- The *Behaviour* of the Occupants. This describes the culmination of all influences, incorporating group/social affiliation, the adoption of specific roles, the response of the individual to the emergency, likely travel speeds, and the ability of the individual to carry out desired actions.

The relationship between these influences is described in Figure 2-2. Each of these might have several separate effects on individual’s actions, involving physical, psychological, and sociological aspects, and indeed many factors will fall under more than one subject heading. These factors will be examined in an attempt to generate an understanding of frequently observed actions during evacuation.



**FIGURE 2-2: INTER-RELATIONSHIP OF THE FACTORS INFLUENCING EVACUATION.**

### 2.3 CONFIGURATION INFLUENCES

The enclosure defines the configurational influence upon the emergency event. It establishes the arena in which the event occurs, and provides many of the relationships that the population develops with each other, and the fire event, by determining the purpose behind an individual’s presence at the event.

Configurational considerations are those generally covered by the traditional building codes and involve building layouts, the number of exits, exit width, travel distance, etc.

#### 2.3.1 REGULATIONS

As building codes all over the world gradually move towards performance-based regulations, building designers increasingly find the fixed criteria of the traditional prescriptive methods too restrictive. This is due in part to their almost total reliance upon configuration considerations. Furthermore, as these traditional prescriptive methods are insensitive to human behavioural or likely fire scenarios, it is unclear if they indeed offer the optimal (or even safe) scenarios in terms of evacuation efficiency.

The physical configuration of the enclosure is governed by regulations that are country specific. The enclosure design is vital to the success of the evacuation, however it is often seen in isolation from the population and from the purpose of the enclosure, as well as from its effect in times of evacuation. The enclosure can have a detrimental effect upon the evacuating population, through designs that incorporate standards which do not reflect the requirements of the population [61].

Prescriptive regulations are in place to ensure basic levels of design and safety (examine the work of Tanaka, who describes regulations used in Australia, France, Japan UK, and USA in some detail [76,77]). These deal with considerations such as,

1. The *minimum number of exits*, which in most countries is two.
2. The *maximum travel distance*, which depends upon the number of directions of means of escape, the layout of the floor area, the building features, the occupancy type, the physical and mental capabilities of the occupants, and the hazard control equipment available.
3. The *common path of travel* of the population, which is considered one of the most important factors, and is restricted in all of the countries. Tanaka explains that,  
*“Two means of escape must be located as remotely from each other as practical to avoid them both being blocked by the same fire”* [77]  
 i.e. they do not share a common path of travel.
4. The *exit capacity*. The number of occupants which can pass through an exit at any one time.
5. The number of *dead end corridors*. The number and length of these is limited, to prevent people being trapped by smoke, and prevent time wastage.
6. The *occupant load*. The expected number of occupants within the structure.

This assumes that the owners and constructors of the structures adhere to the regulations, pre- and post-construction. At the time of several infamous tragedies, the structures did not conform with the regulations [52,53]. In the Beverly Hills Supper Club tragedy the enclosure was provided with far too few exits for the eventual occupancy levels, and therefore did not have the exit capacity to evacuate the large number of occupants safely. At the time of their construction these structures may well have satisfied the requirements of local regulations. However, over the years the addition/subtraction of structural components altered the capacity of the occupants to evacuate safely.

Tanaka criticised the assumptions on which these standards are based, as although they are convenient for the planning of conventional buildings, they do not allow for the violation, even in a small part, of any of the standards. The prescriptive codes make no allowances for violations on the part of the occupants who are assumed to use the building in a predictable and optimal manner. If they adopt an unexpected behaviour, the

regulation's ability to cater for occupant flow is diminished. This is a major factor in suggesting the need for performance based codes.

Occupant behavioural violations may take the form of exit misuse. If some exits are used disproportionately, the efficiency of an evacuation will decrease, as some paths will become overpopulated [62]. The impact this may have on an evacuation has been demonstrated using evacuation models [8]. It was also tragically demonstrated in the Dusseldörf airport fire [75,78,79]. Newspapers reported that people were

*'...jamming main entry points and trampling one another as they ignored instructions to head for emergency exits.'* [78]

This may be caused by a number of configurational and procedural factors including familiarity, signage, guidance of staff, proximity, and a number of other reasons, all of which would upset the expected population flow through the exits. Proulx noted this uneven use of the exits during her investigation of apartment fires, observing that

*"Areas around the elevator and stairs leading to the main exits are seen as familiar. People may use stairs that are less convenient in proximity to their apartment, simply because they spontaneously go to areas with which they are familiar."* [80]

A general set of recommendations has been compiled by the NBI [81], that suggest targets at which designers should aim to encourage a more distributed use of the enclosure. These concentrate upon,

1. The simplicity of access and movement routes.
2. The replacement of stairs with ramps where possible
3. The reversibility of egress systems.

This last point is supported by Sime, who sees the reversibility of egress systems as vital. This is because

*"Far from encouraging a fire exit to be used in an emergency, restriction on their regular use of a route make it less likely to be readily used in a fire."* [61]

Due to the insensitivity inherent in prescriptive building codes, and the abuse to which it is vulnerable, performance-based codes are seen as a more realistic method with which to govern buildings. These also have disadvantages, with the obvious increase in building specific data required to correctly design performance codes, but with this increase in information, largely dealing with the expected movement of occupants, performance based codes are more able to cope with the issue of occupant evacuation.

The regulations determine the minimum expectation of the capacity of the structure to cope with emergency movement. As such it provides the arena within which the evacuation occurs and therefore influences to a large extent the success or failure of the evacuation. However, by addressing this factor in isolation and elevating the configurational influence to the most significant factor, prescriptive codes are making a gross simplification.

## **2.4 PROCEDURAL INFLUENCE**

The procedural influence upon occupant behaviour entails a number of factors. The configurational knowledge of the occupants determines the occupant's ability to receive information from the configuration through either alarm or signage systems. This will affect the occupant's navigational capabilities. The ability of the staff to intervene during the evacuation, and the familiarity of individual occupants with exit availability through everyday use, will both influence evacuation decisions concerning route choice and initial response. These factors and others will be addressed here.

### **2.4.1 ALARM SYSTEMS**

The effectiveness of alarm systems is fundamental to the success of an evacuation. An effective alarm system may not only reduce the time it takes for an individual to react to the emergency, but might initialise a predetermined chain of events which leads to the safe evacuation of the occupants. The factors involved in the alarm system that affects this procedure can be summarised as

- The clarity of the warning
- The believability of the alarm

The clarity of an alarm system concerns the information that the system provides to the population, and whether it clearly denotes the occurrence of an emergency incident; i.e. is it possible for the occupant population to determine the enclosure alarm from other adjacent alarm systems [82]? The level of effectiveness of this process might be improved through the introduction of an IFWS (information warning system) alarm system, which includes a graphical/aural explanation of the event [64,81-84], or through public address systems and pre-recorded messages [79].

In addition to the clarity of information supplied, the clarity of the alarm system also applies to the reception of the alarm signal. This can be affected, especially in traditional

bell alarms, by the location and power of the alarm signal. Members of the population who do not clearly receive alarm information may misinterpret or ignore the message [80].

The believability of the alarm is dependent upon the frequency with which the system is tested on the enclosure population, the frequency of malfunctions, and the frequency of false alarms [82]. The frequency of these events significantly affects the manner in which occupants respond to the signal [29].

The effectiveness of an alarm system goes hand-in-hand with the level of education in the expected actions and responses to the activity of the alarm. The interpretation and reaction of the occupants to the alarm might be improved by implementing modern developments and by using a combination of audible and visual notification, to increase occupant response as well as tailoring the system to react intelligently to the surrounding conditions.

#### 2.4.2 SIGNAGE

As the size of the population involved in the evacuation of unfamiliar enclosures decreases, so the necessity of signage increases to assist wayfinding. Wayfinding is defined as

*“the...notion of spatial problem solving which comprises the cognitive and behavioural processes necessary to reach a destination.”[85]*

In other words, a process involving decision making, decision execution and information processing [85]. This type of activity is especially common in unfamiliar occupancies, with sparse populations, such as hotels [14]. In this respect, the importance in decreasing the population densities is the effect that this will have upon the communication of enclosure information.

The signage system should provide the occupant with enough information to minimise the amount of time spent wayfinding. It achieves this by guiding the occupants along an appropriate egress route [62].

This system must function during both normal and evacuation conditions, which might include high levels of smoke obscuring occupant vision [86].



Different forms of signage from sophisticated, technologically advanced attempts, to the careful design of the enclosure, can aid in the attempt to minimise the wayfinding process. The enclosure itself can assist in the wayfinding process, by presenting a simple and memorable landscape around which to navigate [86].

As with the alarm systems, the information imparted by the signage systems should be appropriate and unambiguous. This should also be in agreement with any other information systems, such as the alarm system or the staff, which are distributing information during the evacuation.

### **2.4.3 ENCLOSURE USAGE**

The structure in which the incident occurs is vital, in that it establishes the relationship that the individual has to the fire in a number of ways. It determines the physical environment in which the incident occurs and it implies a number of social and psychological relationships of which an individual would be aware. These relationships may be part of an overall social structure, such as an employment or familial structure, which is shaped by the usage of the enclosure.

The position of the occupant within this social structure will influence individual activities, by determining their role within the fire event. The roles that occupants maintain outside the evacuation process, i.e. roles that are reliant upon the usage of the enclosure, will be maintained during the evacuation [57,60,65].

The formality of this social structure will also determine the influence of other factors, such as gender, and age, as well as the likelihood of relevant training [87].

The formality of the building environment may determine egress paths, due to the existence of a prescribed procedure that might not exist in a less formal environment. This will have a significant affect upon the egress path which occupants adopt, as during the evacuation the enclosure may be partitioned into specified areas, with occupants inside these areas having pre-specified destinations based on an overall escape strategy [56,65,88,89].

Most importantly, and independently of the formality of the structure, different structures (hotels, hospitals, domestic residences, office buildings, schools etc.) have been found to exhibit patterns of occupant behaviour. These patterns do not include unique or defining qualities, but due to differing information levels and relationships to that structure and therefore other occupants, require people to do predictable activities, but using different priorities, depending on their perception of the fire [44, 57,60, 65,90-95].

The evacuation procedure employed by the individual occupants will therefore be influenced by the use and population of the structure. Each type of structure will present different challenges, depending on the needs and abilities of its inhabitants. This highlights the existence of frequently observed behaviours in evacuations, which have a distinct relationship to the ‘place’ in which the event occurs.

#### 2.4.4 FAMILIARITY

The occupants’ familiarity with a structure is vital in determining the likely individual actions and in formulating effective evacuation procedures. People tend to use familiar routes in egress situations, and through the confidence gained from experience of a building, may defer otherwise expected actions. It is unlikely that occupants will adopt totally unfamiliar paths during an evacuation. As Sime and Kimura point out,

*“People’s exit choice behaviour is closely related to the normal patterns of circulation and configuration of exits” [96]*

identifying the occupant’s trend in ignoring what might be considered to be the obvious available exit for one which is familiar to the individual [79,97,98].

This has implications both for the design of evacuation procedures, and the ability to judge occupant movement from the movement of occupants in non-emergency situations [99]. This is important, especially when one considers the assumptions used in traditional building codes, and as familiarity might encourage exit misuse.

This familiarity may also extend to the relationship between the occupants and the staff or attendants present. Where relationships exist between the staff and the occupants, there is a greater opportunity for the staff feeling responsible for their charges [4, 52,53,100, 101,102].

Familiarity with the enclosure may generate a level of confidence that allows occupants to attempt activities such as fire-fighting or delaying their response. This is because occupants familiar with the enclosure will be aware of the exit position, and will therefore be more confident in reaching them quickly [98].

By assuming that familiarity is a factor in occupant behaviour, we logically legitimise the use of drill movement as an indicator for evacuation movement. This drill movement may not represent the speed of locomotion, but may give an indication as to the preference of egress route [56].

Occupant familiarity with the enclosure is an important consideration in understanding exit choice and the choice of action. It is one of the major factors that undermines the assumption of the building regulations.

#### 2.4.5 STAFF/WARDENS

The role of pre-appointed wardens/staff members during an evacuation can be likened to that of the alarm and signage systems. Their activities are a source of information and guidance during the evacuation, with the added source of assistance; physical intervention. As noted by Donald and Canter,

*“The role of the authority figures is most significant, because by the point that the influence of direct physical cues was strong enough, the time left within which survival was possible was severely limited.” [97]*

indicating the importance of the warden as a significant cue to the event. In this respect, the member of staff might reinforce the occupant’s belief of the severity of the incident [96,97].

Wardens can relay structure-specific evacuation procedures, divulge directional guidance, and act as significant cues to the existence of the emergency. Their effectiveness in these pursuits, depend upon the level of staff training and perceived expertise, the confidence exhibited by the staff in their own abilities leading to a level of assertiveness, and the geographical position of the staff within the building. The performance and acceptance of ‘expert’ actors in the evacuation should not be taken for granted. It will depend upon their actual level of expertise, their willingness to maintain a level of responsibility under extreme conditions and their familiarity with the occupant population [52,97,103-105].

The geographical location of the staff is an important factor in their effectiveness, and is analogous to the positioning of a mobile alarm system [106]. A member of staff who is inappropriately positioned will have a limited effect upon the occupant population irrespective of their level of expertise.

The employment hierarchy within which the staff member finds himself or herself may hinder their performance due to the rigidity of this structure, causing difficulties in information passing. The relationship that an occupant maintains with the members of staff will also affect the occupant actions, as if the sanctions for inappropriate activities, such as causing a false alarm, are harsh, it may cause a delay on the occupant's part to act [95]. It should also be expected that more external staff/experts might intervene during the evacuation, with the necessary benefits/difficulties that this may cause. This will especially be the case during large-scale emergencies [97,106].

The type of information that the 'expert' will be expected to give will be dependent on whether they were internal or external staff. Internal staff may have information that is situation specific, whereas external staff may have a more general expertise in the evacuation field. It is important that the information that is provided by the different types of staff is not contradictory, as this will reduce the benefit of the staff presence, and will cause significant confusion to the occupant population [97]. The perception that the public has of the staff will also affect the acceptance of the advice provided [97].

The activities of the staff will be vital to the safe and efficient egress of the occupants only if the information disseminated is accurate and appropriately received.

## **2.5 THE ENVIRONMENT**

The environmental effects of fire hazards can be separated into three stages. Initially, the fire ignites and grows, prior to the extensive production of heat or smoke. The hazard then spreads, exposing occupants to the smoke, toxic gases, and an increase in temperature. At this stage occupant wayfinding ability and their speed of movement, may decrease due to worsening conditions. Finally conditions worsen to such an extent that if the occupant is exposed to the conditions for an extended period, the occupant will die.

### 2.5.1 SMOKE

In this section smoke will be taken to represent the visible particulates produced in fire effluent. In this sense, we will concentrate on the visual obscuration and psychological impairments that arise in such conditions, the barriers that such obscuration present to individual occupants, with some reference to the respiratory difficulties engendered by the non-irritant particulates [9,57,60,106-113]. The toxic effects of smoke are treated in subsequent sections.

Visual obscuration is *concentration* related, and therefore the effect does not generally accumulate over a period of time [9]. The immediate levels of obscuration will therefore be more important than the cumulative level to which the occupant is exposed.

Smoke has the effect of reducing the speed of occupant movement. The manner in which the smoke affects occupants is dependent upon a number of factors including the gender of the occupant, the thickness of the smoke, and the familiarity with the enclosure [57,60,106,107].

After an initial physiological reaction to the presence of the smoke, there is an acclimatisation to the conditions, followed by a general decline in the condition of the occupant. The speed of this decline is dependent upon the severity of the conditions [69,106].

During an evacuation, smoke can affect the occupant's response in a number of ways. Initially, it can alert the occupant of the fire event, hastening their response. Once the occupant decides to move, the level of smoke in the environment may block off certain exit routes due to the level of obscuration. This obscuration may also decrease the occupant's wayfinding ability, and may also have a psychological impact upon the occupant [107].

The psychological reaction of the occupant to the conditions signifies a general acclimatisation, interrupted by the necessity of new and unusual activities, brought on by the severity of the conditions [69].

The physiological and psychological effects of the smoke effect are gender specific. Male occupants tending to have an overriding physiological effect whilst female occupants have a dominant psychological reaction [9].

Due to the distinctive nature of smoke; it's ability to spread throughout an enclosure, it's visibility and it's role in indicating the severity of an incident, it is important to discuss and analyse the effect of smoke separately from other related conditions. In reality, the effect of smoke upon occupants is connected to those of the toxins and the temperature fluctuations discussed in this section.

### 2.5.2 NARCOTIC GASES

These gases directly affect the nervous and cardiovascular systems; effects which may lead to incapacitation or death. Narcotic gases include HCN, CO and CO<sub>2</sub>. CO<sub>2</sub> is especially important as it causes hyperventilation. This increases the occupant's uptake of narcotic and all other gases, which significantly increases the amount of toxin ingested by the occupant [22,108-113].

The narcotic gases may be modelled using the Fractional Effective Dose approach. In these models it is assumed that the severity of the occupant's condition is related to the narcotic *dose* received from the atmosphere, rather than the concentration received at any specific moment [22,108-113] .

Several Fractional Effective Dose models exist (including those of Purser [108-109,112-113] and Speitel [110,111] ). Each of these models have their strengths and weaknesses, depending on the particular formulations used.

### 2.5.3 IRRITANT GASES

The effects of irritant gases may take two forms. The more immediate of these forms is that of sensory irritation (including extremely sore eyes, coughing, burning sensation in the upper throat and lungs). This form of irritation is unlikely to be fatal [108-109,112-113] but may have a major impact on evacuation efficiency. There may also be a delayed effect, involving the penetration of the irritant gases deep into the lungs. This is far more serious, but tends to have a delayed reaction and would therefore not generally affect the evacuation.

Irritant gases take two forms; inorganic and organic. They include HCl, HBr, HF, SO<sub>2</sub>, NO<sub>2</sub> and the organic gases [22,108,112]. The Fractional Irritant Concentration (FIC) is used as a measure of the irritancy that the occupant is subjected to, in a similar manner to the FED model used to model the narcotic gases [108-113].

The effect of irritant gases are assumed to be additive, with each contributing to the overall effect at different concentration levels [108-109]. Once the FIC, which is expressed as a fraction of the *concentration* required to cause irritation, reaches unity, the atmosphere is considered to be severely irritant [108-113].

There is some difficulty in measuring the term ‘severe’ in relation to the irritant gases. Rodent experiments were used to generate a comparison, which provided a measure against which the environmental levels of irritancy might be compared [108-109].

The influence of the irritant gases are much more difficult to determine than the narcotic gases, due to the incomplete information concerning the constituent parts of irritant gases, and the lack of clearly defined endpoints to the scale of irritant effects [108-109].

#### 2.5.4 HEAT

Occupants may be exposed to heat through the processes of conduction, convection or radiation. During evacuation, occupants are more likely to be exposed to heat via the means of convection and radiation.

There are three mechanisms, by which exposure to heat may lead to incapacitation or death,

- heat stroke, and change in the body core temperature (hyperthermia),
- skin burns,
- respiratory tract burns and psychological effects [108].

Lengthy exposure (more than 15 minutes) to temperatures which are too low to cause skin burns (less than 120°C in dry air, and 80°C in saturated air), affect the body’s core temperature causing hyperthermia. When the core temperature is increased from a normal value of 37°C to 40°C, the occupant experiences ‘blurred’ consciousness (semi-consciousness, dizziness, nausea), and at 43°C, exposure can be fatal within minutes. The time for the core temperature to reach fatal levels is dependent on (a) air temperature, (b) level of occupant activity, (c) amount of clothing and (d) humidity levels.

The second effect that an occupant may suffer due to an increase in the air temperature is surface burns. Unlike the hyperthermia situation, clothing may provide some protection

against surface burns. Pain is experienced by the occupant when the skin temperature at a depth of 0.1mm reaches 44.8°C [108-109].

Finally, damage to the respiratory tract due to burns is strongly dependent on the air humidity. Due to its higher heat capacity, inhaled hot air with a high water vapour content can cause more severe damage to the respiratory tract than dry air at the same temperature. Dry air at 300°C can cause burns to the larynx after a few minutes while humid air at 100°C can cause burns throughout the respiratory tract [108-109].

Exposure to radiation is considered to be concentration (i.e. flux) related. Radiative tenability is considered to be 2.5kW/m<sup>2</sup>. Below this value, exposure can be tolerated for several minutes while above this value exposure is measured in seconds [108-109].

For convective heat, the effect is considered to be dependent on the dose received. A time to incapacitation can be calculated according to the time of occupant exposure to convected heat, at a particular temperature. This calculation is then used to produce a FID of heat. Several FED models for heat exposure exist (including those of Purser [108-109] and Speitel [110-111]). The models predict incapacitation to occur at significantly different levels due to the different data sets upon which they are based. The Purser model makes use of data based upon naked occupants, whereas the Speitel model relies upon data taken from the effects of high temperature upon clothed occupants. As a result the Purser model predicts that incapacitation occurs after a one-minute exposure to 190°C while the Speitel model predicts incapacitation after a minute exposure to 240°C.

## **2.6 BEHAVIOUR**

This section will highlight the occupant behaviour in the light of the factors introduced in the previous sections. These will include the configurational, procedural and environmental factors discussed. In addition, those influences that are brought to the evacuation by the occupants themselves will be introduced, including occupant movement, occupant responses and perception, interactive behaviour, gender, age, occupant ability and disability.

### **2.6.1 BEHAVIOURAL RESPONSE TO CONFIGURATIONAL INFLUENCES**

The configurational influence upon an evacuation refers to the manner in which the occupant relates to the enclosure layout. The configuration determines the quality of the



terrain and the dimensions within which the occupants move. If dysfunctional, the configuration can cause high-density populations, blockages, and exit misuse [114]. As such, the effects of the configuration are fundamental to many of the behavioural characteristics of occupants exhibited during the evacuation, especially those related to movement (see section 2.6.6).

## 2.6.2 BEHAVIOURAL RESPONSE TO PROCEDURAL INFLUENCES

In this section the manner in which the occupant responds to alarm systems, signage systems, staff and how occupant familiarity with the structure influences evacuation is discussed. As well as these issues, the impact of structure usage will be discussed, in particular, the relationships between social structure, enclosure type and occupant behaviour.

### 2.6.2.1 THE EFFECT OF ALARM SYSTEMS ON OCCUPANT BEHAVIOUR

During an evacuation, the purpose of the alarm system is to encourage the occupants to evacuate as quickly (or more accurately, as efficiently) as possible. The amount of information that the system can impart is dependent on the style of alarm used, and the occupant's interpretation of the alarm itself.

For an alarm to have any useful effect, it must be in place, must be used properly and must function. In two occurrences (the Summerland fire and the Beverly Hills Supper Club incident [52-53]) this was not the case. As reported in the official report, during the Summerland fire,

*"Summerland had the means of promptly notifying the public in the building of any fire emergency ...The actuation of the [alarm] system at any public call point would immediately signal to the control room and, after a delay, notify the fire brigade and the public within the building. No effective use was made ...of this equipment, .... Although... a signal reached the fire brigade, no alarm sounded within the building...The probable explanation of this is that the fire had attacked the wiring in the building so that a short circuit was caused."* [52]

Here, the inappropriate protection afforded to the alarm system prevented it from functioning properly. Indeed the fire brigade was eventually notified from outside sources, including passing ships [53].

Even more tragically in the Beverly Hills Supper Club incident, no alarm system was legally required. However the official report found that the provision of an alarm would have certainly been beneficial in avoiding such a tragic loss of life [52].

Glass and Rubin [115] identified the three main problems for the potential evacuee in receiving information from an alarm system. These are :

- *Detection Problem*-Is there a problem?
- *Recognition Problem*- What is the problem?
- *Discrimination Problem*-Is the problem distinguishable from other problems?

As they stated,

*“Effective communications assumes not only the capability to transmit a complex set of messages but a high degree of assurance that the appropriate messages are received and understood by those that are threatened by the fire” [115]*

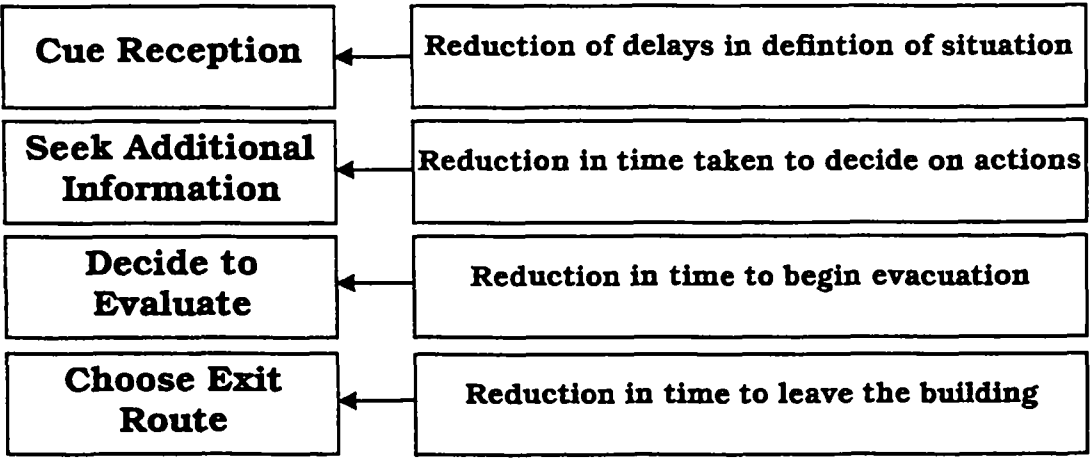
The occupant's response to the alarm is *mainly* affected by their ability to distinguish between the occurrence of a fire alarm and other forms of alarm. In the work of Tong and Canter [82,100] 45% of the sample population (taken from a street survey of 71 random individuals) could not distinguish between the occurrence of a fire alarm and a number of other less vital warning systems (e.g. car alarms, security alarms etc.). An explanation for this misinterpretation might lay in a large proportion of the population having hearing difficulties. However, this proportion was not great enough to explain this phenomena. This misinterpretation might result in the delaying of investigation or evacuation. This problem would be especially apparent in urban areas populated by a large number of occupants, where the noise level is high, and the sound of an alarm is frequently heard.

This lack of response is made worse when the alarm is not supported by additional cues. This was noted by Geyer et al who found that only 13% of respondents questioned who were initially made aware of an event by the alarm, believed that the sound of a fire bell was a *real* emergency [116].

To compensate for the inability of occupants to distinguish between different forms of alarm, more sophisticated approaches than the traditional bell alarm may be introduced.

In modern information warning systems (such as informative fire-warning (IFW) systems), the alarm signal is localised through the use of a number of cues, identifying the occupant's present location, the location of the fire event and the required exit, thus removing the possibility of confusion. Bellamy [83,84] investigated just such an introduction upon a sample of 48 female and 48 male occupants taken from a range of occupations, and found that it produced an 81% response rate, compared with a 13%

response rate measured for people responding to a traditional alarm (a constant ringing sound). This is comparable to the figure of 17%, produced by Pauls in his examination of evacuations from high rise structures and the occupant response to traditional alarm systems [99]. It was noted however, that the high response rate observed by Bellamy, may have been due, in part, to the novelty of the new technology, and may, in time, have decreased as the occupants became accustomed to the new system. The effect of the introduction of such a system upon the reaction and decision-making process of the occupants is described by Sfintesco et al [117] in Figure 2-3.



**FIGURE 2-3: THE IMPACT OF INTRODUCING AN IFW SYSTEM UPON THE DECISIONS AND RESPONSE OF THE OCCUPANTS [117].**

The introduction of an IFW system may not only increase the likelihood of occupants responding but may also increase the probability of them responding appropriately. The results of the Geyer et al support this hypothesis, suggesting that the use of an IFW system increase the likelihood of the occupant perceiving the event as a genuine fire *and* therefore evacuate in response to it [116].

In other occurrences, public address systems are used to augment a standard alarm bell system. These are used to supply additional information considered necessary for safe evacuation, and have been found to be far more effective than the more traditional bell alarm [118]. However, if the information is unclear, the system may prove a hindrance. In an examination of multiple occupancy evacuations, only 15% of the population understood the information provided, and this was seen as at best useless and at worst a hindrance to a speedy evacuation [26]. In an examination of the quality in vocal warning systems, Keating and Loftus found that variations in voice quality, pitch and volume, as well as content, all had an effect on cue perception [119]. The idea that the manner in which instructions are delivered may effect the occupant’s reaction is further examined in section 3.6.2.5.

In their examination of the occupant reaction to different forms of alarm warnings including PA systems, Proulx and Sime found some significant differences in the results generated [13,118]. Through examining the occupant’s reaction to the sounding of a traditional bell alarm and to the provision of different levels of information across a public announcement system, a difference in the response of the occupant’s was established (see Table 2-1).

**TABLE 2-1: DATA PRODUCED DURING EXAMINATION OF RESPONSE TO DIFFERENT ALARM TYPES [13].**

<i>Evacuation</i>	<i>Time to start to move</i>	<i>Time to clear station</i>
<i>Bell only</i>	8 min. 15 sec.	Exercise ended 14 min. 47 sec.
<i>P.A.(told to evacuate)</i>	1 min. 15 sec.	10 min. 30 sec.
<i>P.A.(told to evacuate and the existence and location of the fire)</i>	1 min. 30 sec.	5 min. 45 sec.

From this example the provision of information and the detail of the information provided is demonstrated as being a factor in the response of the occupant population.

The findings of Proulx and Sime were supported by tests conducted at the Fire Research Station who found that only 13% of those examined responded to an alarm bell, 45-55% responded to textual messages, while 70% responded to voice or picture alarms.[120, 121]

Pre-recorded messages are also used as part of alarm systems. The sound of a voice-even a recorded voice-giving directions being considered to convey more authority than a simple bell. However in using such systems operators must ensure that the correct message is broadcast. The importance of this was tragically demonstrated in the Dusseldorf airport fire where incorrect messages were broadcast which directed occupants to the seat of the fire rather than to safety [79].

As well as the occupant’s ability to differentiate between the forms of alarm, the ability of the occupant to receive the information imparted is also vital.

The position of the alarms, especially traditional alarm bells, should be carefully examined to maximise their impact on the population prior to the evacuation. Of

particular interest is the effectiveness of the alarm in notifying the occupants of the incident and imparting an optimum level of information concerning the event.

Proulx found that simply positioning alarm bells in corridors did not ensure that they could be heard by the population prior to the evacuation [80]. Also, those moving along these corridors in which the alarms were positioned would suffer the deafening noise during the evacuation, which might adversely affect their escape. She concludes,

*“It is obvious that the location of the alarm bells has a major impact on the audibility of the alarm.” [80]*

The National Fire Protection Association recommended noise levels for smoke detectors/alarms of 85 dBA for occupants with standard hearing and 100 dBA for occupants on medication or with hearing difficulties. It was found that the effectiveness of such alarms could easily be enhanced by the use of visual aids [122,123]. These principles also apply to more modern alarm systems, including those with graphic and text messages, so that the population for which the information is intended receives it at an appropriate time.

The occupant’s interpretation of the seriousness of the alarm, i.e. whether the alarm reflects an actual incident or another less serious event, is an important influence on the occupant’s response.

In an examination of occupant responses to the evacuation of a multi-storey structure, Tong and Canter [82,100] studied the responses of occupants. Of the occupants who did not respond to the alarm, 23% of them believed that the alarm was a test, 14% believed it was a malfunction, and 2% believed it was a malicious false alarm. As Reissner-Weston pointed out,

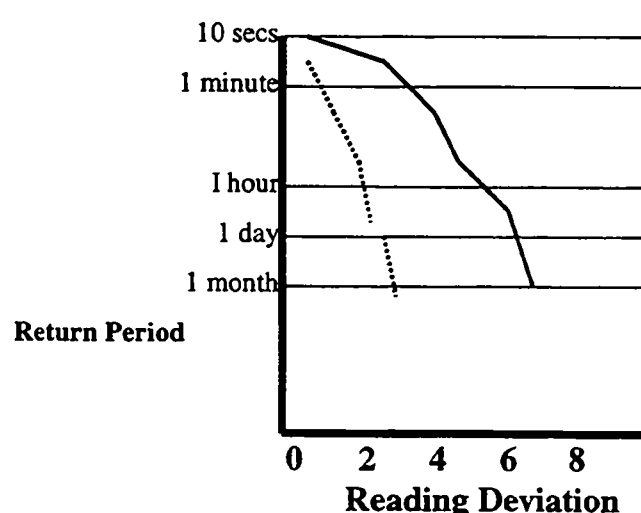
*“The omnipresence of traditional fire-bells and their respective false alarms in everyday life, could explain why such a low proportion of the sample population interpreted its warning as genuine. The previous behaviour of the alarm must therefore be taken into account when deciding upon the subjects interpretation of the warning, since this can affect the trust and consequently the individual subjects interpretation of the alarm.” [29]*

Pigott [64] identified three reasons behind the occurrence of false alarms, which he believed to be of equal importance:

- The environment (heat, moisture, dust, etc.)

- The alarm equipment (electrical and mechanical)
- Human interference [64].

A recent development in tackling false alarms is the manufacture of computer based AFD (Auto Fire Detection) systems. Initially, these systems continuously monitor an enclosure, obtaining data relating to the regular environmental status. For an alarm to be activated this control data is compared against the current environment to determine whether an alarm signal is warranted. This then becomes a control against which present data is compared (see Figure 2-4). This has many advantages as these emergency parameters may change throughout the day, and might be manually altered to account for localised activities (such as smoke from a kitchen, a smoking room, etc.). The AFD systems, due to the database of information, can provide the origin, the spread rate and the density of the smoke, through comparison with the pre-established data [64]. Another important function of the AFD system is that it is capable of examining the functioning of the system, noting the existence of localised fluctuations that might indicate the replacement of a component.



**FIGURE 2-4: TYPICAL SENSOR DEVIATION FROM MEAN PLOTTED AGAINST LOG TIME COMPARING ENVIRONMENTAL DATA WITH CONTROL DATA [64].**

Kozeki et al [124] have developed a system for use in a multi-purpose high rise structure, whose inhabitants have different levels of disability. This system incorporates a multi-element fuzzy expert system. The system not only detects and determines the significance of the event, but warns the occupants individually depending upon their needs, alerts the fire brigade, and guarantees a level of communication throughout the event. Such a system avoids the type of communication breakdown seen in the New York Trade Centre evacuation [106].

This system identified the importance of identifying the whereabouts and existence of occupants who require rescuing, and guaranteeing that evacuation information reached them, through the positioning of alarm devices (and PC terminals in this case), and the use of a dispersed information system. This system incorporates advanced features to determine occupant locations including a link between all door status and fire staff, and the presence of motion detectors in occupant's rooms.

The overriding responsibility of alarm systems is to inform the occupant population of the fire event. With the introduction of more sophisticated equipment, not only is this done more successfully, but real-time and more extensive information can be imparted.

It is unclear however, whether the advantages observed with the introduction of new technology is due to their novelty, or to some underlying feature. Once these introductions become more popular, it is possible that the problems that arose in distinguishing traditional alarms, between and within enclosures, may arise in relation with more modern sophisticated alarm systems.

#### **2.6.2.2 THE EFFECT OF SIGNAGE**

The importance of signage systems to the occupant is to reduce the amount of time they spend wayfinding, through the provision of information and directions that lead the occupant to an appropriate exit route, or safe area. However, even the most well-designed signage systems cannot compensate for badly designed architectural structures. As Garling et al confirmed,

*“It may be questioned whether any sign-posting system, however elaborate, is capable of overcoming the difficulties imposed by a low degree of differentiation, poor visible access, and a complex spatial layout.” [125]*

This sentiment is supported by the findings of Bryan, who reported that only 8% of the occupants evacuating were entirely dependent upon sign for the provision of directions [126].

The process of wayfinding is especially important in hotels, large office buildings and structures in which the stairways are irregularly used, where the occupant may not be familiar with the entirety of the structure. Ozel [14] related a person's ability to 'wayfind' in an emergency to the accuracy of that individual's cognitive map. This is created and

maintained according to the signage provided, the complexity of the space, and the evidence of the exits. As Nelson et al point out,

*“Wayfinding efficiency decreases as the layout complexity increases.”[62]*

One aspect of this process was highlighted in the Summerland incident where the lack of appropriate signage hindered the movement of the population. The affect of this was to cause significant amounts of congestion at a small number of escape routes, due to their overuse. This was detailed by the authors of the official report who claimed that ,

*“We have no specific evidence that there were any directional signs guiding the public towards the exits. We think it possible that some people on the upper floors were not aware that there was any way down other than the flying staircase by which they had come up.”[53 ]*

It was at this staircase that severe crowding was recorded [53].

The effect of the signage, and the effectiveness of the enclosure in assisting the wayfinding process is closely related to the complexity of the enclosure, and the presence of distinguishing landmarks inside the enclosure. This might include statues, pictures, distinctive colour schemes, and a number of other architectural structures[62,85].

It is desirable for the occupants to spend as little time as possible wayfinding. In such a manner, the wayfinding procedure is most successful when,

- The routes are simple, but memorable.
- The exit points are evident.

Paulsen [86] investigated the movement of a group of 46 men and 33 women, inside an unfamiliar two-storey structure filled with smoke, and attempted to discover the occupant’s memory of their egress route, and their temporal awareness through the use of periodic questioning. In comparing more traditional signage with modern techniques, it was found that ERI (The Escape Route Information System), had a significant effect on the wayfinding ability of individuals, in a similar manner to the more sophisticated IFWS alarm systems. The information imparted and the inclusion of visual and tactile information, all had an effect on the evacuation times of the population (see Table 2-2).



**TABLE 2-2: COMPARISON BETWEEN SOPHISTICATION OF BUILDING SIGNAGE SYSTEM AND EVACUATION TIMES [86].**

Configuration of Escape Route Information	Evacuation Time(s)
Discontinuous Visual ERI	65.6
Semi-Continuous Visual ERI	30.5
Continuous Tactile ERI	91.7
Cont..Visual ERI/High Luminance	45.9
Cont..Visual ERI/Low Luminance	51.7
Combined Tactile And Visual ERI	44.9

Within aircraft, floor proximity lighting has been in use since the Manchester B737 fire of 1985 [127,129]. Floor proximity lighting is intended to lead passengers to their nearest exit route in the event of the cabin filling with smoke. Similar systems could be used in buildings, utilising floor lighting or luminescent paint.

Signage should not be considered as an isolated system within an enclosure. The enclosure itself is a fundamental part of the signage system, as it can provide a number of memorable cues vital to the wayfinding process of individuals, especially in unfamiliar or difficult conditions.

The signage system requires a similar form of analysis to that required by alarm systems. Occupants may be thought of as initially being alerted by alarm systems, and possibly given information concerning their egress routes. The occupant, once alerted to the danger, then requires more detailed information to evacuate, which is provided by the signage system. This information will relate to the occupant’s present location and the route required from that specific point. It is therefore important that there exists a level of continuity between the two systems.

**2.6.2.3 THE EFFECT OF THE ENCLOSURE USAGE**

The most significant influence that enclosure usage has upon occupant behaviour is through defining the relationship that the occupant has with the enclosure, and with the other occupants. In this respect, the influence of the enclosure is not causal, but will instead point to the likelihood of certain types of social structures being present inside the enclosure.

Where the enclosure usage is causal, is in the formality of the structure itself and the possible existence of pre-defined fire procedures. As Chubb [88] identified, the level of training and fire-safety practice is important in determining fire recognition (but not

necessarily the correct action). As most training is building specific, the role of the structure is important in determining evacuation actions. The imposition of evacuation procedures upon a population, might not only determine the egress path, but might also affect the specific actions taken by individuals [57]. Wood observed that the more training an individual had received, the more likely the person was to attempt to control the threat and therefore less likely to leave [57].

The absence of these procedures has an increasingly large impact in relation to the complexity and diversity of the structure. The Summerland case provides an example of a complex multi-use facility where no global evacuation procedure was in place. This led to spontaneous and conflicting advice to be provided. This led the official investigators to report that,

*“...It is an essential duty of the management to establish and maintain a practical procedure .... It is not easy to do this and the requisite procedure can certainly not be improvised during an emergency...At Summerland the maintenance of a proper system of evacuation was rendered more difficult because there was a rapid turnover of staff throughout the season. In the emergency there were errors of judgement, errors of action and errors of inaction. They were all human errors and failings and are not to be derided by us who were not involved at the time. In the absence of prior thought and organisation, all this was expected.”[53]*

This passage not only identifies the absence of any organised procedures, but points out the importance of maintaining any procedures against becoming out of date or unfamiliar. It also identifies a primary role of the inclusion of procedures; that of accounting for wholly expected human failings and the subsequent mistakes.

In formal structures with large populations, there exists a choice between two forms of evacuation procedure; namely an uncontrolled and a controlled evacuation [56,89]. An uncontrolled total evacuation has no prior practice or procedure, and depends mainly on the goodwill and survival instinct of the population. It is the cheapest and simplest option, and provides little or no information to the evacuating population.

A controlled selective evacuation has a predetermined series of events, inside which population subgroups have allotted evacuation times and exits. This form of evacuation will generally require practice drills, and involve staff appointed as fire wardens to redirect evacuees. During this form of evacuation, the evacuation procedure (e.g. when particular groups of occupants start to evacuate, etc.) is critical.

Pauls examination of the data concerning the implementation of these two forms of evacuation, involving a tall office building, resulted in insignificant differences in the evacuation times produced [56]. However, the level of stress on the evacuating population was not investigated, and there may have been significant differences between the two, with uncontrolled evacuations requiring a large degree of individual initiative.

Glass and Rubin conclude that given the implications of uncontrolled evacuation from complex environments, that the total evacuation is not viable, especially from high-rise buildings [115]. Given this is the case, provisions have to be made for the safe passage or refuge of the occupants involved. These include the immediate limitation of the fire size, the provision of safe refuge, the use of sprinklers, the maintenance of structural integrity, the control of the passage of smoke, the existence of an emergency control centre and total protection plan should be implemented [115].

As noted earlier, an important influence exerted by the enclosure is over the social structures present within it. The social structures present in an enclosure will largely be *determined* by the enclosure's use. This use will require social structures of which occupants will be a member.

Through comparative studies of occupancy types, including domestic, multiple occupancies and hotels, Canter [65] found that the behavioural patterns of the occupants were different in ways which could not be explained simply through the physical influence of the building. As Canter noted,

*"[People] relate to the type of 'place' in which the fires occur...[the term 'place'] implying a combination of social and physical processes that give any setting its particular qualities." [65]*

As we can see in Table 2-3, these factors are not exclusive, and may contribute to a variety of different outcomes, in different situations. These are some of the most apparent observations, which he categorised into building types.

In *multiple occupancies/hotels*, occupants tend to be less familiar with the layout of the entire structure and other occupants, either through being a guest in a hotel, or through

living in an apartment, hence having a local as opposed to a general geographical understanding of the structure. In such circumstances, there is significant wayfinding, and through the possibility of the cues being distant and ambiguous, a high degree of investigation. In these circumstances the configuration and procedures have important roles to play in occupant wayfinding.

**TABLE 2-3:REPRESENTATION OF SOME OF THE VARIABLES AFFECTING BEHAVIOUR IN THREE OF THE BUILDING TYPES, IDENTIFIED BY THE RESEARCHERS ABOVE [57,60,70].**

Hotels/Multiple Occupancies	Domestic fires	Hospital fires
1. Awareness not due to alarms. Communication is critical, due to increased contact with others.	1. Misinterpretation of information, unless contact with fire.	1. Early investigation, as there was always somebody awake, on the ward, etc..
2. Complex interaction with others, as a function of potential sources of information. No/very little non-adaptive behaviour observed.	2. Unstructured investigation, leading to encountering smoke	2. Whereabouts instead of existence, important due to more complicated evacuation procedures.
3. Investigation required due to misinterpretation, giving rise to direct contact. Assistance given between guests/occupants.	3. Action as a function of fire growth and location.	3. Routes usually specified by staff. Transfer of information specified through the employment hierarchy
4. Early actions based around information seeking and wayfinding. Misinterpretation of cues, due to unfamiliarity, and possible distance of the event.	4. Gender being an important variable in determining action	4. Evacuation through smoke occurs.
5. No re-entry. Little attempt to fight fire, unaware of fire location.	5. Confirmation of Information, given by others.	5. The influence of the incapacitated.
6. Instructions from staff followed. Lack of obvious role in social setting.	6. Re-entry and fire-fighting relatively commonplace.	

In the MGM hotel fire in 1980 [60,90], the contact of occupants with other unfamiliar members of the population was a factor during this evacuation, as it tended to provoke occupants into preparing themselves for such an activity (e.g. getting dressed). The complexity introduced by the heterogeneous nature of the occupant population should be considered when determining evacuation behaviour. This might involve a number of social/familial/economic groups, each of which has separate evacuation agendas (see section 2.6.4). The diversity in the geographical location of occupants within the structure lead to many of the occupants not being notified about the incident through the alarm system, but from other occupants, or members of staff. This fact highlights the altruism exhibited in such situations, and the lack of precise knowledge that occupants have access to, leading to an inaccurate idea of the position of the fire event.

In a *domestic environment*, the emotional attachment to the property and to the other inhabitants produces specific actions; namely re-entry, notification of others, fire-fighting, and evacuation. Bryan found that

*“The behavioural response of the occupant who after safely leaving the building turns around and re-enters, has been observed most frequently in the residential fire incidents.”[91]*

In an examination of the interviews of 584 participants involved in 335 residential fire incidents, investigated by U.S. fire department personnel, Bryan found that 27.9% (162/584) attempted re-entry [60,91]. This re-entry was either to fight the fire, to retrieve personal property, to obtain information concerning the state of the fire, or to notify others. All of these actions suggest the required emotional attachment to the building and the occupants necessary to encourage re-entry. It must be emphasised that this behaviour is not totally restricted to one type of occupancy, but might be expected in enclosures to which occupant’s feel a high degrees of attachment.

In a comparable U.K. study, Wood [57] examined 952 fire incidents and noted that 43% of the participants attempted re-entry. The Wood data comprised predominantly of domestic fire incidents (over 50%) with 17% occurring in factories, 11% in flats/multi-occupancy dwellings, 7% in shops and 4% in other institutions. The results generated by Wood are therefore expected to be dominated by the influence of the domestic fires. He noted three general types of reaction to fire: these are individual or group-based evacuation, fire fighting/ containment and communication.

**TABLE 2-4: OCCUPANT BEHAVIOUR NOTED IN BRITISH AND U.S. STUDIES. THE 'CR' FIGURES REPRESENT THE SIGNIFICANCE OF THE DIFFERENCES BETWEEN THE TWO SETS OF DATA, WITH THE ASTERIXES IDENTIFYING THOSE SIGNIFICANT AT 1% LEVEL [60].**

<i>Behaviour</i>	<b>British %</b>	<b>U.S. %</b>	<b>P<sub>1</sub>-P<sub>2</sub></b>	<b>SE<sub>P1-P2</sub></b>	<b>CR</b>
<i>Evacuation</i>	54.5	80.0	25.5	2.3	11.1*
<i>Re-entry</i>	43.0	27.9	15.1	2.3	6.6*
<i>Fire Fighting</i>	14.7	22.9	8.2	1.7	4.7*
<i>Move through smoke</i>	60.0	62.7	2.7	2.3	1.2*
<i>Turned back</i>	26.0	18.3	7.7	2.0	3.8*
<i>Total Occ(N=5)</i>	2193	584			

Some other differences are evident between the Wood and Bryan findings (see Table 2-4). These differences can be partly explained by the differences in the original sample, but also highlight cultural differences between the two sample populations. The likelihood of performing specific activities during a fire incident may therefore be

partially dependent upon the societal influences, in the form of norms and mores, which are evident in the society of residence.

An important example demonstrating re-entry behaviour occurred in the Arundel Park incident [57]. The fire occurred at a time of a church outing involving a close-knit community; a closeness similar to that expected in a domestic household. During the event, a third of the population were seen to re-enter the structure; a structure with which they had no particular affiliation. The reasons cited for re-entry were the finding of loved ones, informing the others of incident, and offering assistance to others (those conditions seen in most domestic incidents). The incident was unusual in the high level of attachment between the entire population, and a near disregard for the structure. This is important as the group were familial (or equivalent), and yet unfamiliar and unattached to the building, and yet still re-entered the structure, highlighting the importance of the occupant relationship, in the decision-making process.

Due to the social structures inherent in a domestic household, gender appears to have important implications upon the activities of individuals [57,60,65,92]. Interest in the spread of the fire and the damage to the property, encourages investigation and therefore direct encounter with smoke/fire. This incurs a variety of responses, dependent upon the gender and status of the individual. This attachment also urges the occupant to confirm the existence of the fire. Bryan [91] found that 14.9% of the male population searched for the seat of the fire, compared to 6.3% of the female population, within domestic environments. Conversely, 11.4% of the female population contacted the fire services as their first response, whereas only 6.1% of the male population attempted this activity. Bryan noted that the male actions of searching for or fighting the fire are matched by the female activities of initiating an alarm and evacuating.

This indicates the complex relationship which can occur between a number of factors (in this case a domestic environment and gender), which then combine to influence occupant behaviour. The influence of gender upon occupant behaviour is further investigated in section 3.6.7.

Horasen and Bruck examined behaviour during an evacuation from a *secondary school* and found that it produced behaviour specific to that structure [128]. By questioning the

students they found a reliance on the acceptance of those around them. Although this behaviour might be exhibited elsewhere, it might not be as prevalent as in a situation full of adolescents, due to importance of peer pressure.

*“It is quite clear that students faced with a class of peers suggesting no action are significantly less likely to initiate risk reducing behaviour such as ‘leave building immediately’ and ‘tell everyone’ than if they were alone in the classroom. In the class situation the type of fire cues do not play a significant role in determining behaviour. In contrast when a student is alone the type of fire cue does influence behaviour”[128]*

The possibility of looking cowardly or foolish in front of peers is an important consideration in the initial behavioural reaction to environmental cues. Other significantly common activities were for occupants to leave the building immediately, and to inform others of the incident. This behaviour might be generalised to other similar structures with a rigid structure imposed upon a dominated, juvenile population.

*Hospitals* are another structure with distinct behavioural patterns, involving a strict employment hierarchy and an occupant population of mixed abilities. A study concerned with the evacuation of 30 patients [94] (in fact actors simulating patients), discovered that non-ambulatory evacuees had a disproportionate effect on the evacuation, and therefore had to be dealt with separately (see section 2.6.6.3). The researchers concluded that,

*“The optimal strategy is that in which the patients are only taken as far as is necessary to clear the ward. The order in which activities are done is not so critical.” [94]*

indicating the importance of pre-determined fire procedures, similar to those identified by Pauls [56,89]. Due to the spread of people throughout the building, detection and investigation of the incident occurs early in the evacuation scenario. Information is then transferred according to a rigid staff structure, relating to the location and intensity of the event. This is required due to formality of the evacuation procedure.

Gender has far less of an effect on occupant behaviour in a rigid economic structure, as it's effect is superseded by the staff hierarchy and the individuals position in relation to it. For example, a female nurse is more likely to see herself firstly as a nurse in a position of responsibility, and then as a woman. The patients are less likely to be treated/to react differently according to their gender than they are according to the severity of their ailment.

The different occupant reaction to the event is highlighted by Lerup et al [87] in their examination of evacuations in ten nursing home facilities. They saw the possibility of occupants performing specific responses to the surrounding events as being dependent upon their relationship to the staff hierarchy (see Table 2-5 and Table 2-6).

**TABLE 2-5: INFORMATION GATHERED BY LERUP CONCERNING THE BEHAVIOUR PATTERNS OF HOSPITAL STAFF [87].**

ACTIONS	OBSERVATIONS	PERCENTAGE
INVESTIGATE	23	24.5
ALARM	39	41.5
ATTACK	10	10.6
FLIGHT	6	6.4
RESCUE	14	14.9
NO ACTION	2	2.1

**TABLE 2-6: INFORMATION GATHERED BY LERUP CONCERNING THE BEHAVIOUR PATTERNS OF PATIENTS [87].**

ACTIONS	OBSERVATIONS	PERCENTAGE
INVESTIGATE	16	25.8
ALARM	17	27.4
ATTACK	4	6.5
FLIGHT	17	27.4
RESCUE	1	1.6
NO ACTION	7	11.3

Patient destinations are determined by senior staff, whose instructions are disseminated by lower ranking staff. Movement through smoke occurs due to the existence of prescribed evacuation procedures, the suitability and age of the building forcing such actions, and the delay in the passing of information. In those structures where disabled or non-ambulatory occupants are expected in large proportions, appropriate evacuation procedures should be expected to account for their specific requirements.

Edelman et al [95] examined the evacuation of a five-storey care facility of 250 occupants. They interviewed 22 elderly occupants (10 men and 12 women). They identified the importance of the staff on the interpretation of cues by the occupants. Once an initial cue of the event had been provided, and was then confirmed by a member of staff, the likelihood of a patient responding was far greater.

*“Possibly the most important determinant of the respondent’s behaviour...[was] the behaviour of the staff members...The social structure in nursing homes, as in other total institutions, places authority, power and responsibility in the hands of the staff. Staff members represent information and direction and often assist residents in the simplest activities of daily living. It is logical that residents would follow the advice of staff, particularly during an emergency.”[95]*



There are a number of other types of building, generally categorised as *public buildings*. The behaviour observed in such enclosures varies, depending on the particular use and configuration of the building.

The more general category of public buildings incorporate a number of building types, such as restaurants, offices, etc. The complexity of the behaviour and events involved in these incidents is diverse. Evidence concerning this behaviour is based largely upon the following events [65].

1. Andersons Department Store(1960,UK)[65]
2. Beverly Hills Supper Club(1977,USA)[51,52]
3. Woolworth Department store(1979,UK)[93]
4. Summerland recreation complex.(1973,Isle of Man)[53,54]

From these events the following activities can be discerned.

Initially, the ambiguity and misinterpretation of cues, and their increased importance is evident, due to the spectrum of influences and activities that might occur. This might be due to the decrease in familiarity in comparison with domestic incidents and the dimensions of the structure. The occupants have a tendency for investigation, and movement towards the fire event, as the event might be obscured or distant providing less obvious cues. Sime noted in his examination of hotel evacuations that the decreased levels of occupant familiarity cause a distinct form of occupant behaviour. He claims that

*“The distances moved [by guests], while not excessively more than might be required notionally to reach a point of safety (i.e. 90ft), are characterised by ‘backtracking’ behaviour.”[54]*

Berlin [129] defines the ‘backtracking’ of occupants as where occupants begin an activity, such as entering a room, prior to realising that the action must cease leading to them retracing their steps.

The response time to the event is dependent upon the pre-fire activities, which influences the location and the perception of event cues. Of course, in the more complicated environment of public buildings, there exist a greater number of possible pre-fire activities, than in other building types, due to their size and complexity. The events in public building are particularly susceptible to the effects of group behaviour (see section

2.6.4), and the influence of authority figures (see section 2.6.3). This can be attributed to the distribution of occupant types within a number of social/economic hierarchy.

Possibly the most complex of all structures in which to estimate behaviour or evacuation routes are the complex, *multi-use office blocks*. The events of the New York Trade Centre [106] incident demonstrates the complexity, and the regionality of these effects. In such occurrences, it might be appropriate to treat the building as a number of separate entities, with distinct characteristics and populations.

The importance of the structure in which the event occurs cannot be overstated. The presence/absence of formal evacuation procedures, the activities of occupants, and the pressure of the hierarchical social structure will all influence the actions and responsibilities of the occupants, and the effects of personal attributes, such as gender, upon the individual. By supplying the overarching social structures, the building usage may be considered as providing fundamental sociological evacuation factors.

#### 2.6.2.4 THE EFFECT OF OCCUPANT FAMILIARITY

Familiarity can in some respects be seen as a function of the enclosure's use, the social structures present, the quality of the signage and the level of wayfinding within a structure. Familiarity can effect the behaviour of the occupants in that instead of heading towards the expected 'nearest' exit, as assumed by environmental determinists, they instead move toward another less obvious exit. This has serious implications for the implementation of building regulations, which assume a rational approach to exit choice based on distance. Donald and Canter echoed this principle in their examination of the King's Cross tragedy when they found that,

*"In the King's Cross fire,... the actions of people can be understood most readily by taking account of their normal behaviour in that situation."* [97]

Therefore, the patterns of normal building use have an effect on evacuation behaviour, causing exit routes which carry high loads in normal use to be used most frequently in an evacuation. This was also observed in the Düsseldorf airport fire [78,79]. This might have serious implications for the occurrence of blockages at over-subscribed exits, and exit routes.

Pauls [99], saw this effect replicated in a number of simulated emergency evacuations (drills), which appeared a good basis for predicting occupant movement in a fire emergency. He indicates the importance of examining the regular social and physical environment, to predict their actions in a difficult, and possibly unique situation. This could be seen during the King's Cross fire, where passengers, when attempting to evacuate, adopting routes which appeared closely related to those usually used [97]. As noted by Gardner,

*"To improve the effectiveness of escape routes it should be recognised that the value of an exit is not only related to its width or distance of travel from the most remote part of the room. A route, that is regularly used by the building occupants to enter and leave the building will be of much more value than a fire exit, used in an emergency"[120]*

In an examination of an evacuation of an eight-storey office building, Horiuchi et al [98], saw a sharp difference between the actions of those occupants familiar with the structure and those who were not. These differences effected the actions, the routes taken, and the success in reaching the exit. The most obvious difference in activities, was the preponderance of familiar occupants who chose to fight the fire, in the knowledge that they could find their way out, whereas unfamiliar occupants immediately attempted to evacuate. This demonstrates the confidence that familiarity breeds, allowing occupants the belief that the knowledge of an escape route gives them the opportunity to carry out fire-fighting activities.

Sime [4,101] compared the activities of occupants and staff members in their actions, and related these with their level of familiarity with the building and with each other. Individuals under threat, seek security with familiar routes and people.

*"As long as an exit is not seriously obstructed, people have a tendency to move in a familiar direction, even if further away, rather than use a conventional unfamiliar fire escape route."[4]*

In an examination of the statements of the victims in the Summerland fire [94], the relationship between the staff and the customers appeared to be distant with little or no emotional relationship established. This became evident when examining the egress patterns of the two populations. The customers evacuated through exits which were familiar to them through daily use, which tended to be the main exit. The staff chose exits for the same reasons, but their daily use involved using fire exits as short cuts in their daily routine. Therefore the distribution of exit use was skewed in that the staff used the fire exits and the customers used the main exit. The staff did not perform what

may have been expected to have been their obligation, to lead the customers to safety, which may have been due to the distance of the relationship between the two groups, or to the quality of the staff training. As noted by Sime,

*"In general, being a member of staff was a pre-determinant of (a) location and (b) the exit used. "[54]*

In the Beverly Hills Supper Club incident [52], there was a much closer relationship between the staff and customers, as a table attendant was responsible for a table and dealt with all of their orders, establishing a higher degree of personal contact. Once the incident arose, the table attendants guided the customers to safety, during the evacuation. This highlights,

1. The importance of familiarity on exit choice.
2. The effect of this on the activities and performance of the staff in relation to the customer population.

As Tong and Canter identified,

*"Equivalent role groups will not always display identical patterns of response; rather it is the nature of the relationship between the two different role groups that sometimes shape behaviour."[82]*

The occupant's choice of exit is related to the routes used during normal movement. Occupants will not spontaneously move towards new routes because they are denoted exit routes, and will, on the contrary, often travel a greater distance towards those routes with which they have a greater familiarity.

#### **2.6.2.5 THE EFFECT OF STAFF/WARDENS**

The effectiveness of the staff in conveying information to the occupant population is dependent upon a number of factors. Their effectiveness in these pursuits, depend upon

1. The level of staff training and therefore the expertise exhibited in evacuation stewarding. This expertise might be location specific or, less usefully, consist of a general expertise in evacuation.
2. The confidence of the staff in their own abilities leading to a level of assertiveness,
3. And the geographical position of the staff within the building.

Sime and Kimura [96] examined the simulated evacuation of two lecture halls, and found that the lecturers were a key factor in determining the evacuee's eventual choice of exit. Contributory factors to this influence were the authority and assumed knowledge of the lecturers, and the fact that the lecturers were clearly seen and heard.

Those involved in assisting evacuations, will not consist solely of the internal staff, but will be joined by a number of external actors with whom they will have to liaise, and who will be expected to assist in the evacuation. Proulx described this almagamation of assistance during the New York Trade Centre incident, when the

*“Management, fire department and the media should be prepared to provide information as precise as possible to the occupants.”[106]*

This consideration would be particularly important in large-scale evacuations involving a large number of people.

A pre-defined fire procedure would involve the staff adopting roles related to their position in the employment hierarchy. The formality of this staff hierarchy can have an adverse effect upon the evacuation. In an examination of the deaths of 21 occupants evacuating from a nursing home, the requirement of the staff to pass information along the management line slowed down the reaction to the fire event [65]. The formality of the staff hierarchy can also effect other occupants. Edelman found that on questioning evacuees from a nursing home, some were reluctant to use certain fire exits as they triggered alarms, which would have had incurred the wrath of a feared member of staff [95].

The reliability of the internal fire wardens/senior members of staff to act appropriately in an emergency, is dependent upon the level of training received and the relationship that these staff have with the evacuating population (as observed in the Beverly Hills incident) [52]. In the Summerland tragedy, the absence of management procedure and intensive training forced individual staff members to devise responses to the incident. This generally lead them to fight the fire. Unfortunately, although unselfish, this act delayed alerting members of the public, preventing them from evacuating earlier in the fires development. This was cited as a major influence upon the number of fatalities in the official report [53]. This behaviour was mirrored, on a smaller scale, in the Beverly Hills Supper Club incident [52].

In an extensive study of evacuation behaviour in health care facilities, Bryan et al [130,131] found that nursing staff, who had been instructed in evacuation procedures, and maintained a familiar relationship with the occupant population, performed their tasks even in **'situations of high risk'**.

In contrast to the reverence with which the nursing staff are held, the low esteem with which the underground staff, are held, adversely effected the evacuation procedure, at an underground station. Donald and Canter [97], in their examination of the King's Cross incident found that the public perception of the underground staff, significantly influenced the reaction to the their instructions.

In normal use, the underground staff ensured the public traversed the station, with little significant social interaction; there was little or no opportunity to interact with the same member of staff, and even if this occurred, it was short-lived. Assistance was generally given only if requested. Unfortunately the advice of the underground staff, which might have saved a number of lives, was superseded by that of the police, due to the assertiveness with which it was given, and the perception of the passengers of the status of the police in such a situation. Traditionally, there was little respect for the underground staff, as they were seen as ill-informed and were therefore almost powerless to influence the path of the evacuation

*"Thus the public's social representations of the different bodies involved may have a strong influence on their actions in the emergency." [97]*

Police are generally seen as trustworthy in times of emergency due to their experience, and the assertiveness with which their instructions are delivered. Unfortunately, the staff with local knowledge (the underground staff) was ignored to a far greater extent. Police took command, but redirected and advised the population in questionable ways, including the request to leave a departing train and the evacuation of a large number of people to an area close to the fire. The police advice adversely effected those occupants' chances of survival. A number of people would have escaped the tragedy if they had boarded the train situated at one of the platforms. Police officers instructed them to leave, and then guided them into a ticket hall. Six of these passengers were killed and many were seriously injured. This highlights the fact that what people consider to be appropriate actions are a combination of expected actions in response to perceived cues, and the redefinition of these cues by figures of authority. These figures of authority, in

this case the underground staff, advised occupants but were ignored whereas the police, a conflicting source of information, provided advice which was universally accepted, even though their knowledge of the station was less extensive than the underground staff. The role of the police was crucial, due to the response and respect of public. In this situation, the general evacuation principles of the police were accepted and applied, whereas the more appropriate local knowledge of the underground staff, was ignored.

The perception of the staff was also an important factor in the Beverly Hills Supper Club incident, where instructions to evacuate were delivered by a relatively junior member of staff. As noted by Feinberg et al [49,50], once instructed, most patrons followed the directions. However some maintained their course, ignoring the information the information due to the lack of seniority of the member of staff [49].

Different communication problems were evident in the incident at the Who concert in Ohio. Here 11 people were killed due to excessive overcrowding and the resultant crushing. As Johnson states,

*“Those who continued to push forward from the rear were unaware of events near the front. Difficulty in communication within the crowd...was compounded by its high density. Patrons faced an additional communication problem in redefining the crowd situation from the police and other officials. Although most patrons who were interviewed defined the efforts to get through the doors as flights to safety, police officers and security guards continued to see them as gate-crashing efforts after the surge had begun.” [50]*

Here, due to the police's perception of the crowd, communication was limited, preventing action being taken that might have restricted the tragedy. This has a number of similarities with the Hillsborough incident, in that because behaviour based around survival mimicked the usual forms of behaviour (e.g. rushing towards the exit to gain access to the concert) it was largely misinterpreted or ignored [49,50,51].

Muir et al [103] attempted to further demonstrate the effectiveness of assertive *crew* staff, in their attempts to impart evacuation advice. A test was conducted as to whether the effectiveness of the cabin crew in airline evacuations is dependent upon the position of the cabin crew and the assertiveness exhibited. They investigated this through evacuations involving one, two and no cabin crew, and attempted to determine whether the performance and number of cabin crew influenced the evacuation process. Another variable, which they examined, was the level of competition between evacuating

passengers, and its effect upon their evacuation times (this is examined in greater detail in section 2.6.6). To achieve this, a proportion of the evacuations was competitive, and some were collaborative. This was achieved by supplying the fastest evacuees with a monetary reward, therefore encouraging a competitive evacuation. The results of this simulation lead Muir et al to the conclusion that,

*"Cabin crew behaviour was found to be of great importance during both the initial stages of the evacuation and also as the egress progressed."[103]*

**TABLE 2-7: MEAN EVACUATION TIMES FOR THE FORTY-FIFTH INDIVIDUAL (TIME IN SECONDS) (COMPETITIVE) [103].**

Cabin crew	1 door		2 door	
	Mean	SD	Mean	SD
2 assertive	58.0	6.2	36.6	2.2
1 assertive	63.2	21.0	36.6	4.4
2 non -assertive	76.6	8.1	40.6	2.0
None	79.7	9.4	42.2	1.4

The assertiveness of the crew seems particularly important when the level of co-operation between the passengers was diminished (examine Table 2-7 and Table 2-8). In more competitive situations, where people’s actions may adversely effect those around them, instructions delivered assertively appear to align their actions, diminishing the negative effect of a competitive environment (examine Table 2-7).

**TABLE 2-8: MEAN EVACUATION FOR THE FORTY-FIFTH INDIVIDUAL (TIME IN SECONDS) (CO-OPERATIVE) [103].**

Cabin crew	1 door		2 door	
	Mean	SD	Mean	SD
2 assertive	57.1	5.3	34.3	2.1
1 assertive	59.8	10.5	36.0	4.7
2 non-assertive	74.1	6.5	39.6	3.5
None	70.6	4.0	39.1	2.2

In the tests involving assertive cabin crew, 75% of participants felt that the crew had aided their escape in comparison to only 47% of those assisted by non-assertive cabin crew group.

*" the results clearly indicate the importance of having cabin crew who adopt assertive behaviour"[103]*

As identified in these examples, assertiveness can have an influential effect on the evacuation procedure. This effect may have a positive [103] or negative [97] influence depending on the accuracy of the information and the manner in which it is delivered.

The occurrences at the Beverly Hills Supper Club incident demonstrated the significance of the staff in an evacuation, especially in their ability to relay specialist knowledge or through their unique view of the situation. There is little doubt that the actions of a single junior member of staff during this incident minimised the number of fatalities. Once



made aware of the incident the staff member immediately instructed other members of staff around him to exit. He then went into the crowded Cabaret Room (the scene of the vast majority of the fatalities), examined the situation and then climbed on a chair. At this stage the patrons were completely unaware of the incident. During his interview with the investigators he described his actions,

*“The first thing I did was I ask them to look at the exit sign, turn around and look at the back and you will see a green exit sign. I want you to all notice that exit sign and I want you to look at the other corner of the room and there will be another exit sign...I want the left hand side of the room to go out of the exit sign I am pointing to now...I want the right half of the room to go out of the other exit sign in the corner of the room. I said, ‘There’s a fire in a small room on the other side of the building...I don’t think there is any reason to panic or rush, you should leave.*  
*“[49,52]*

This action, while successfully redirecting the patrons to separate exits, also provided the necessary information for them to define the situation. This may have accounted for the low rates of reported ‘panic’ behaviour [49,52]. Even here, however, the perception of the information had to be reinforced by the staff member reiterating the requirements.

As with the position of signage and alarm systems, the position of fire wardens is a vital component in their overall effect upon the evacuation. The New York Trade Centre evacuation involved the evacuation of some 100,000 occupants, of which six people were killed and 100 injured. In an investigation of this incident, Proulx [106] noted that a number of fire wardens were called away from their predetermined locations due to what they believed were local emergencies. By doing so, they were unable to communicate information to a number of evacuees. In addition, senior staff publicly criticised and overruled junior staff during the evacuation, lessening both the public’s confidence in the junior staff and their confidence in themselves.

As with all other occupants the activities of the staff population will be effected by the conditions surrounding them and the relationship that is maintained between themselves and the surrounding occupants. However, the occupants will be looking towards the staff for reliable and appropriate advice/actions that may not always be forthcoming. This will be the case whether those responsible are trained fire wardens, senior members of staff, or staff involved in a less rigid occupational structure.

The procedural factors highlighted above are instrumental in determining occupant actions during an evacuation. As such, they are vital in understanding the possible actions, which might be available to the occupant during the different stages of the event.

One common feature to all of the procedural features is that they will have been determined prior to the evacuation. The building usage, the placement of the alarm/signage systems, the training and familiarity of the staff and the familiarity of the occupants with the enclosure will all have been determined *prior* to the fire event. Therefore, for some of them at least, it is possible to improve the efficiency of the evacuation process through careful consideration and design.

### **2.6.3 THE EFFECT OF ENVIRONMENT ON OCCUPANT BEHAVIOUR.**

The influence of the environment upon occupant behaviour includes the effect of smoke, heat, irritant and narcotic gases. These fire hazards may have a physiological or a psychological effect upon the occupant's behaviour, and the level of this effect may be dependent upon a number of occupant attributes, including age and gender.

#### **2.6.3.1 SMOKE**

The perception of the fire is important in the choice of action that the occupant chooses in response to the danger. This perception is enhanced if the danger is experienced first hand and in a majority of cases this will be through an individual experiencing smoke. The presence of smoke influences the way in which a person decides to act, by both increasing the perceived risk, and introducing movement barriers to individuals. Again people's response to smoke is determined by their relationship to the structure and familiarity with the structure, so that familiarity might encourage movement through smoke if the geography of the structure is better understood [57,60]. Bryan identifies,

*“The principle variables influencing an occupant's decision to move through smoke appear to be recollection of the location of the exit, and ability to estimate the travel distance required; secondary variables are the perception of the severity of the smoke; the smoke density; and the presence or absence of heat.” [60]*

The recollection of exit location can be enhanced by appropriately placed signage (see section 2.6.2.2), and by memorable/landmark architecture [56], thus encouraging movement through the smoke.

From his investigation into 952 fires (see section 2.6.3.2), Wood [85] identified several factors which encouraged movement through smoke. These included being male, an extensive presence of smoke, being at home, the fire occurring during the day-time and being familiar with the building itself (see Table 2-9).

These factors are different from the actual physical considerations of the smoke, which might lead to the total or partial incapacitation of individuals (see Sections 2.6.3.2/2.6.3.3), as well as decreased visibility.

TABLE 2-9: FACTORS AFFECTING MOVEMENT THROUGH SMOKE[57]

Category		Probability of moving through smoke(%)
Gender	Male	64
	Female	54
Smoke spread	Extensive	64
	Less Extensive	53
Environment	Domestic	64
	Employment	52
Time	Day	65
	Night	56
Familiarity	Complete	61
	Less than Complete	51

Wood found that in his study, 60% of the population was seen to move through smoke. In a comparable American study [60], in which Bryan examined 335 mainly residential fires, 63% attempted the same task. Table 2-10 shows the extents to which people were willing to move through smoke in such circumstances (refer to section 3.6.2.3).

TABLE 2-10: COMPARISON BETWEEN BRYAN’S AND WOOD’S DATA CONCERNING OCCUPANT REACTION TO SMOKE [57,60].

Visibility distance(ft)	Visibility distance when occupant’s moved through smoke		Visibility distance when occupant’s decided to redirect	
	Wood’s study(%)	Bryan’s studies(%)	Wood’s study(%)	Bryan’s studies(%)
0-2	12	10	29	32
3-6	25	17	37	22
7-12	27	20	25	22
13-30	11	32	6	18
31-36	3	2	1	1
37-45	3	34	1	0
46-60	3	7	1	5
>60	17	7	1	0
Total Occupants	1316	322	1316	322

From Table 2-10 it is apparent that occupants are prepared to move through smoke, even at relatively low levels of visibility. This evidence seemed to be supported by Proulx and Fahy in their examination of the New York World trade Centre evacuation, where 84%

of the population attempted to move through smoke [106]. This high figure might have been in some part due to the position and severity of the event. They found that

*"Recent human behaviour studies have shown that people will move through smoke , but this incident demonstrated that people will not only move through smoke, but people reported that conditions got worse as they kept going"[106]*

Obviously, although these investigations are extensive, they only provide a snapshot of the likely occupant behaviour. As such, the *trends* are of more interest than the probabilities of performance.

In a separate investigation Brennan [107] examined the accounts of the movement of 29 people (19 females/10 men) through smoke, during an evacuation in a multi-tenanted office in Australia. The population was made up of a diverse set of ages, ranging from 29 to 77 years. Using the Behavioural Sequence Interview Technique, the evacuees recounted their experiences for analysis.

**TABLE 2-11: AGE AND SEX OF PEOPLE WHO RETREATED FROM HEAVY SMOKE[107].**

Age range	Gender	
	Female	Male
20-39	0	1
40-59	4	0
60-79	6	3

During the evacuation, all of the occupants moved towards the only known exit, and proceeded to attempt an escape, even though smoke was evident at the top of the exit. Reasons cited for retreating from the exit were the sight of smoke and awareness of its potential threat, the reduction of visibility, and physical problems with breathing and mobility (see Table 2-11). The data generated seemed to indicate, in accordance with the work of Wood [57], that, generally, elderly females were more likely to retreat from smoke than young males.

Once the decision has been made to move through smoke, the psychological and physiological impact of this decision should be examined.

Jin, in a seminal study [9], tested for emotional instability under smoke conditions, using mental arithmetic as an index for emotional instability. This was achieved by exposing the subject to an environment affected by smoke and heat. The subjects ability to carry out mental arithmetic while traversing the experimental area was taken as an indication of the physiological and psychological effects of the smoke/heat.

The experiment population was made up 17 housewives and 14 male students from a local university. The ages ranged from 20-51 years. Some protection from the smoke (a white smoke generated from burning Japanese cedar crib chip) was provided in the form of wet towels. This was believed to shield the participants from 90% of the smoke. The results indicated that,

1. The subjects became accustomed to the conditions after initial physiological problems (eye irritation, for instance). The ability to answer questions correctly therefore increased when the individual acclimatised (see Figure 2-5).
2. The walking speed decreases in proportion to the distance from the entrance. The variance in walking speed based on gender is only significant when thicker smoke is evident, where the velocity of women decreases more noticeably slower. This might have due to the greater physical impact of the conditions.
3. Emotional instabilities affected by smoke were found to be different between male and females, with males tending to have a dominant physiological reaction to the conditions, whereas females had a dominant psychological reaction. The conditions did have an affect upon the occupant's ability to perform mathematical calculations. Those that remained in the corridor suffered according to the instability index.

This lead Jin to declare that

*"The emotional instability caused by physiological factors, such as smoke irritation, is found to be important as well as a psychological unrest under high irritant smoke."* [9]

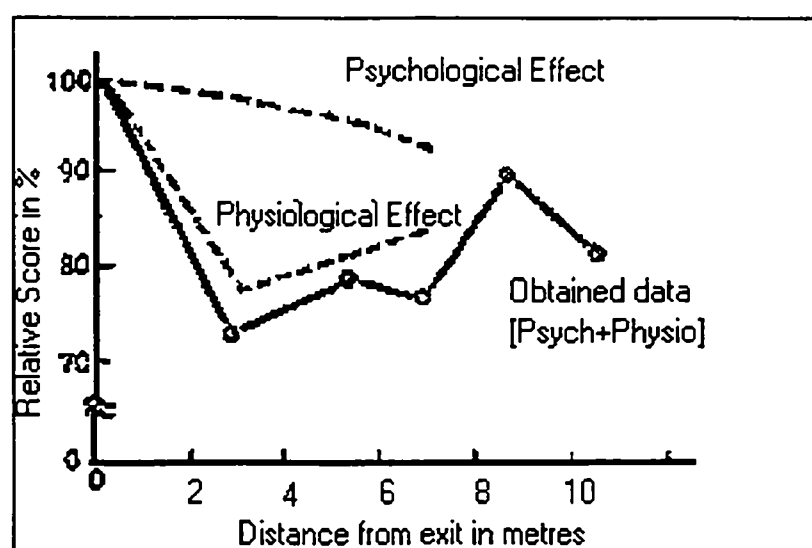
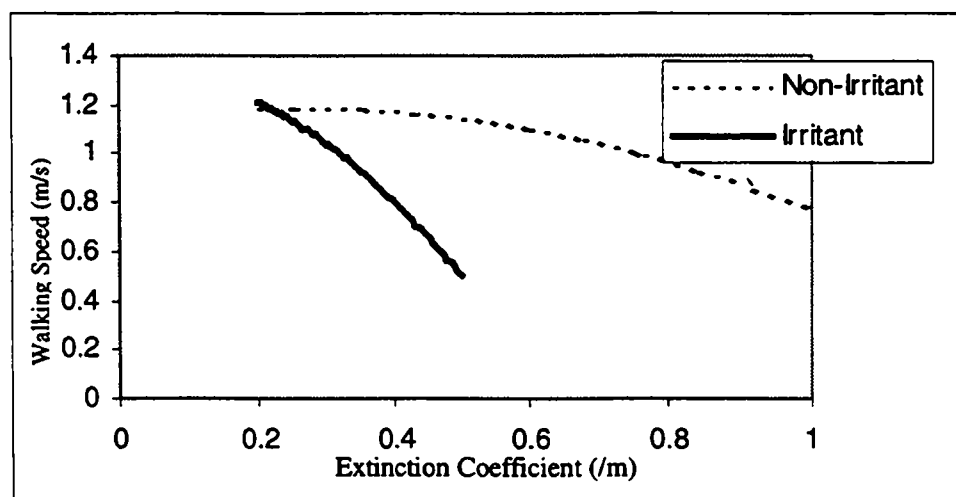


FIGURE 2-5: COMBINATION OF EFFECTS ACCORDING TO JIN [9].

Most importantly, Jin found that the combination of physiological and psychological factors had an affect upon the occupants. The gradual psychological disorientation increased throughout the experiment, whereas the occupants gradually acclimatises to

the initial severe irritation of the conditions. The solid line (in Figure 2-5) shows the relationship between the attainable distance from the entrance and the correct answer rate. The level of acclimatisation was dependent upon the severity of the conditions in the corridor. As the intensity of the smoke rose, so the occupant acclimatisation fell, so that eventually, the occupant would be unable to cope physiologically, or psychologically.

Jin [10] also conducted a series of experiments concerning the physiological effects (relating to visibility and movement) of non-irritant and irritant smoke, upon occupants. This was achieved by filling a 20m corridor with highly irritant wood crib generated smoke, and then with non-irritant smoke generated from kerosene. The subjects were asked to travel from one end of the corridor to the other, identifying when they could see a fire exit sign.



**FIGURE 2-6: THE WALKING SPEED OF OCCUPANTS THROUGH IRRITANT (SOLID LINE) AND NON-IRRITANT (DASHED LINE) SMOKE (REDRAWN FROM THE ORIGINAL [10]).**

The significance of these effects can be seen in the recorded occupant movement speeds. As noted by Jin [10], both the irritancy and the density of the smoke has an affect upon an occupant's walking speed. Figure 2-6 shows the gradual decline of the walking speed through non-irritant smoke as the density of the smoke is increased, whereas in irritant smoke the gradient is far steeper. This was explained by Jin as being caused by the erratic movement of the occupants due to their inability to keep their eyes open [10].

Jin's results suggest that in non-irritant smoke, walking speeds reduce to 0.3m/s in smoke with an optical density of 0.5m (extinction coefficient of 1.15), while in irritant smoke, the walking speed is reduced to 0.3m/s at an optical density of 0.22m/s (extinction coefficient of 0.5).

The results produced by Jin were supported by Purser [113] who reaffirmed the importance of visibility upon potential walking speeds and upon the tenability limits of

enclosures. He postulated that the visibility required for successful evacuation would differ given the size of the enclosure (see Table 2-12). Similar suggestions were made by Wood [57] and Jin [11] based on occupant familiarity with the enclosure.

TABLE 2-12: REPORTED EFFECTS OF SMOKE ON VISIBILITY AND SUBSEQUENT BEHAVIOUR [ 113]

Smoke Density and irritancy OD/m (extinction coefficient)	Approximate Visibility	Reported Effects
none 0.5 (1.15) non-irritant 0.2(0.5) irritant 0.33 (0.76) mixed	unaffected 2m reduced 3m approx	walking speed 1.2m/s walking speed 0.3m/s walking speed 0.3m/s 30% people turn back rather than enter
Suggested tenability limits for buildings with: <ul style="list-style-type: none"><li>• Small enclosures and travel distances</li><li>• Large enclosures and travel distances</li></ul>		OD/m 0.2 (visibility 5m) OD/m 0.08 (visibility 10m)

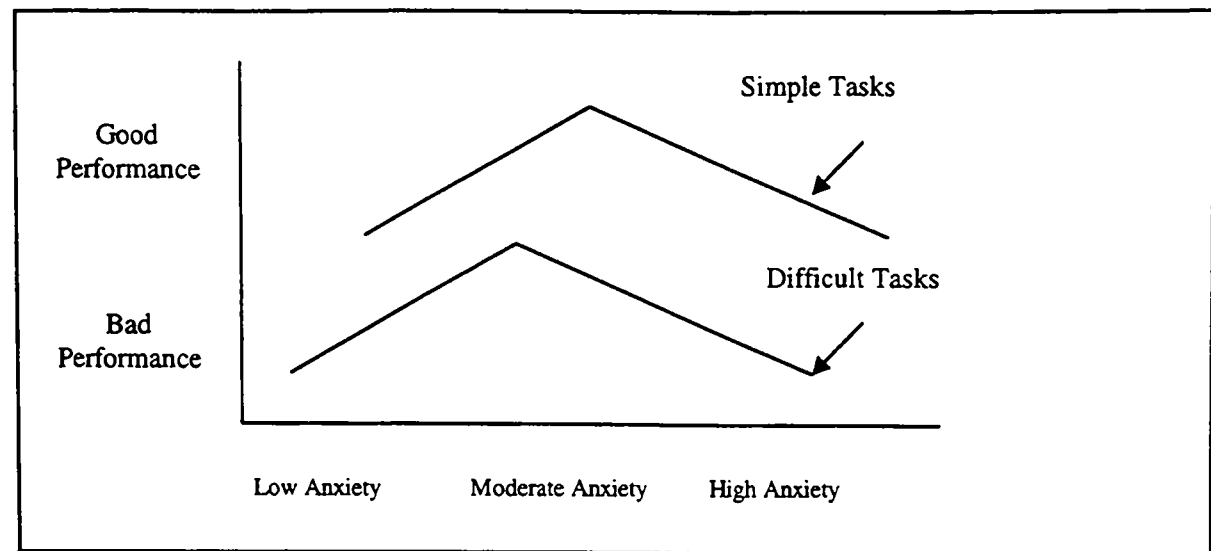
This discussion highlights an important consideration in understanding occupant movement when smoke is encountered. Both the physiological and psychological aspects of traversal may be impaired during movement through smoke. To accurately model such behaviour, the movement through smoke should ideally involve the possible disorientation, and psychological difficulties implied by Jin’s work.

Marrison and Muir performed an examination of the smoke and heat on the movement of passengers in an aircraft emergency [69].

They found that the introduction of smoke/fire limited the number of the exits through the barrier effect of the smoke. Due to the production of toxic fumes and the reduction of visibility, a degree of disorientation was observed, similar to the psychological decline identified by Jin, such that

*"Smoke and fire have the potential to limit the number of exits available for egress and produce toxic fumes, factors which will consequently induce certain behavioural responses."*[69]

These conditions produced the need for novel responses, which heightened the occupant anxiety in the passengers producing a psychological effect (see Figure 2-7). This requirement of the occupants to initiate novel activities required by obscuration causes an increase in anxiety amongst the affected occupants. This effect was modelled upon the work of Yerkes and Dodson [69]. In such a manner, Muir et al agrees with Jin, in that the importance of smoke is not limited to physiological effects.



**FIGURE 2-7: THE RELATIONSHIP BETWEEN LEVELS OF ANXIETY AND PERFORMANCE FOR BOTH SIMPLE AND DIFFICULT TASKS [REPRODUCED BY MARRISON AND MUIR FROM YERKES-DODSON,1908][69]**

### 2.6.3.2 NARCOTIC GASES

When inhaled the narcotic gases cause incapacitation and in extreme cases death. These gases attack the central nervous system causing reduced awareness, intoxication and reduced escape capability. Prolonged exposure (several minutes in some cases) causes loss of consciousness and eventually death. Exposure to narcotic fire gases is the main cause of death in building fires. The effects of some of the major fire gases may be summarised as follows [132];

#### *(i)CO-Carbon Monoxide:*

This is produced when any combustible material burns incompletely or in reduced oxygen. It is always present in fires and can reach extremely high concentrations. Concentrations of several thousand parts per million (ppm) are not uncommon.

When CO is inhaled, it is absorbed by the blood from the lungs and combines with haemoglobin to form carboxyhaemoglobin (CoHb). This reaction inhibits the absorption and hence the transport of oxygen to the body tissue. This reaction may take the following forms,

10 - 20% CoHb generally causes headache,

30 - 40% CoHb generally causes severe headache, nausea,  
vomiting and collapse,

50 - 100% CoHb generally causes death.

However, values as low as 20% are known to have caused death in some victims. It is necessary to consider the original state of health of the victim and their level of activity during exposure. Angina can reduce fatal level dramatically.



(ii)HCN-Cyanide:

Produced by the combustion of Nitrogen (N) containing materials such as wool, silk, polyurethane foams, nylon, leather, acrylics and some plastics. Levels of 3 mg/litre are normally fatal, however levels as low as 1 mg/litre have resulted in death and people have survived levels as high as 7 mg/litre. An atmospheric concentration of 200 ppm will induce rapid collapse and death.

(iii)CO<sub>2</sub> -Carbon Dioxide:

This is produced by the combustion of any fuel. The effects are partially due to the exposure concentration and partially the dose received. CO<sub>2</sub> produces HYPOXIA - a reduction in the amount of oxygen available for tissue respiration. It also has a tendency to increase the respiration rate (breathing rate), thus increasing the rate of uptake of other toxic fire gases and it is itself toxic. The occupant reactions, related to the percentage of CO<sub>2</sub> in the environment are

3 - 6%	respiratory distress,
6 - 7%	dizziness, bordering on loss of consciousness,
7 - 10%	loss of consciousness.

(iv)Low O<sub>2</sub>-Oxygen:

All fires will consume O<sub>2</sub>. If the compartment is not well ventilated the concentration of O<sub>2</sub> can drop dramatically. The effects of low O<sub>2</sub> hypoxia are partly concentration related and partly dose related. The effects, expressed in relation to the amount of O<sub>2</sub> available in the environment, are,

20.9 - 14.4%	slight loss of exercise tolerance,
14.4 - 11.8%	reduction in mental task performance, reduced exercise tolerance,
11.8 - 9.6%	severe incapacitation, loss of consciousness,
9.6 - 7.8%	loss of consciousness, death.

The physiological effect of narcotic gases can be modelled using one of the Fractional Effective Dose (FED) models that not only incorporate the toxic effects of smoke, but a number of other toxins which would be evident in such an environment. *These models assume that the effects of certain fire hazards are related to the dose received rather than the exposure concentration.* The model calculates, for these agents, the ratio of the dose received over time to the effective dose that causes incapacitation or death, and sums these ratios during the exposure. When the total reaches unity, the toxic effect is predicted to occur. As the FED approaches unity occupants' ability to escape may be reduced making it more difficult for the affected occupant to escape.

However, these models are difficult to validate, due to the ethical and technical difficulties posed by such a process.

The FED model of Purser [108-109,112-113] considers the toxic and physical hazards associated with elevated temperature, HCN, CO, CO<sub>2</sub> and low O<sub>2</sub> and estimates the time to incapacitation. The fractional incapacitating dose (FID) for each of the agents is calculated as follows:

$$FICO = 3.317 * 10^{-5} * CO^{1.036} * RMV * \frac{t}{D} \quad (1)$$

where  $t$  is the exposure time (minutes) and RMV (intake) is the minute volume (litres/minute). This equation is unreliable for small adults or children, due to the nature of the original sample.

$$FICN = e^{\frac{CN}{43}} * \frac{t}{220} \quad (2)$$

This equation for FICN is unreliable outside the range 80 - 180 ppm HCN and finally,

$$FIO = \frac{t}{e^{8.13 - 0.54 * (20.9 - O_2)}} \quad (3)$$

Another effect that CO<sub>2</sub> has is to increase an exposed person's RMV and thus increase their rate of uptake of other toxic gases. The FED model considers the combined effect of these agents (FIN) in the following way,

$$FIN = (FICO + FICN) * VCO_2 + FIO \quad (4)$$

where,

$$VCO_2 = e^{\frac{CO_2}{5}} \quad (5)$$

is a multiplicative factor which measures the increased uptake of CO and HCN due to CO<sub>2</sub>-induced hyperventilation. When FIN or FICO<sub>2</sub> equal or exceed unity, the person is assumed to be incapacitated.

While the Purser model is typical of FED models, other formulations have been suggested. Speitel [110-111], for example has developed an alternative model. In addition to the quantities specified in the Purser model, Speitel considers the gases, HCL, HF, HBr, Acrolein and NO<sub>2</sub>. Furthermore, the expression for the CO contribution to the FED calculation is significantly different from that specified in the Purser model.

Both the Purser and Speitel models incorporate a factor that takes into account the increased respiration rate that results from the presence of CO<sub>2</sub>. The hyperventilation factor, has an identical formulation in both models, and is used in the Purser model to represent the increase in uptake of CO and HCN and in the Speitel model it serves a similar function for CO, HCN, HCL, HF, HBr, NO<sub>2</sub> and Acrolein. A modified version of the VCO<sub>2</sub> equation has been suggested by Purser [109] of the form,

$$VCO_2 = \frac{e^{0.1903 * \% CO_2 + 2.004}}{7.1} \quad (6)$$

### 2.6.3.3 IRRITANT GASES

The evacuation modeller is interested in the severity of the effects upon occupants that occur during the evacuation. As such the delayed or long-time injuries that can be caused by irritant gases, will be ignored in this discussion.

The formulation of a reliable occupant response to irritant gases is hampered by poor quality data. This is due to an incomplete understanding of the irritant gases present in smoke. At present 20+ irritant gases have been identified, but this figure is not believed to be definitive [108-109,112-113]. These include HCl, HBr, HF, SO<sub>2</sub>, NO<sub>2</sub> and a number of organic gases.

At low concentrations the presence of irritant gases affect the sensory and upper respiratory organs. This can increase the level of obscuration, and cause mild difficulty in breathing and a burning sensation in the nose and throat. At high levels of concentration these effects become more severe, and may cause incapacitation. It is unlikely that these effects alone will cause death [108-109,112-113].

Jin [9] demonstrated the importance of considering the effects of irritant gases, by examining the movement of volunteers through non-irritant and irritant smoke. Through non-irritant smoke, volunteers behaved as though they were moving through darkness, at a speed of 0.54 m/s. When irritant gases were introduced this movement dropped significantly (see section 2.6.3.3).

As highlighted previously the important effect of irritant gases is that which reduces the occupant's ability to evacuate, or eventually leads to incapacitation.

A measure for this effect was developed by Purser [108-109,112-113]; the Fractional Irritant Concentration, which represents the level of irritant gases as a fraction of that required to cause severe irritation. One of the major problems producing such a measure, is in defining the level at which the irritation becomes severe. Attempts have been made to test the level of irritancy on a rodent population that was subjected to irritant gases, and then the data was extrapolated to the relative human condition [113]. This correlation between animal irritation and extinction was demonstrated to be a valid one [113]. This led to the creation of the RD<sub>50</sub> measure, which indicates the time required at a specific irritant concentration to reduce the respiratory rate by 50%. This form of measurement enabled a more accurate scale for the FIC to be developed.

If the FIC reaches unity the occupant is said to be severely affected by the irritant gases, to the extent that the occupant movement rate declines. Using the available data, the levels at which irritant gases are supposed to become severe are in Table 2-13.

TABLE 2-13: CONCENTRATION LEVELS OF IRRITANT GASES, AT WHICH UNITY IS REACHED IN THE FIC MODEL [108-109,112-113]

Toxic Gas	Concentration
HCl	200ppm
HBr	200ppm
HF	120ppm
SO <sub>2</sub>	30ppm
NO <sub>2</sub>	80ppm for 5 minutes, 25ppm for 30minutes.
Total Organics	0.5 OD/m

Assuming that these factors are simply additive, the irritant concentration, FIC is given by

$$FIC=FIC_{HCl}+FIC_{HBr}+FIC_{HF}+FIC_{SO_2}+FIC_{NO_2}+FIC_{org} \tag{7}$$

These effects are dependent upon the exposure dose, which can be derived by the concentration and exposure time.

One of the problems with the FIC is that it assumes that the effect of the component irritant gases are simply additive, without producing experimental data to support such a claim. Also, the manner in which occupants react to the irritant gases may differ, and at present these different levels are not taken into account.

### 2.6.3.4 HEAT

The occupant may experience heat, either through conductive, convective or radiated heat sources. The sensation of heat perception and the possible effects of exposure to these different forms of heat produce similar results [108-109,112-113]. For the purpose of evacuation modelling, conductive heat exposure is less important due to the occupants general movement away from the fire event.

Heat affects the evacuating occupants in a number of ways. By lengthy exposure (more than 15 minutes) to temperatures which are too low to cause skin burns (less than 120°C in dry air, and less than 80°C in saturated air), the body core temperature may increase causing hyperthermia. When the core temperature is increased from 37°C to 40°C, the occupant experiences 'blurred' consciousness (semi-consciousness, dizziness, nausea), and at 42.5°C, the effect would be fatal. Occupants wearing clothing serves only to exacerbate the problems of overheating.

The second effect that an occupant may suffer due to an increase in the air temperature is surface burns. In contradiction to the problems incurred in overheating, clothing may provide some protection against surface burns. Pain is experienced by the occupant when a temperature of 44.8°C is experienced at a depth of 0.1mm [108-109,112-113]. As Purser describes,

*"Pain therefore occurs when the difference between the rate of supply of heat to the skin surface exceeds the rate at which heat is conducted away by an amount sufficient to raise the skin temperature to 44.8 °C."* [108-109,112-113]

The extent, location and depth of the surface burn will determine whether the surface burn leads to localised pain, incapacitation or death. Although clothing does have an important effect on the extent of surface burns, the formulae implemented by Purser, assume the effect of temperature upon naked skin, to account for unprotected areas, specifically the head. The increase in temperature of the skin may be calculated as follows, assuming a constant radiant heat source,

$$T - T_0 = \frac{2Q * \sqrt{t}}{\sqrt{\pi * k * \rho * c}} \quad (8)$$

where  $T$  is the final temperature of the skin at 0.1mm depth,  $T_0$  is the starting temperature at the same depth,  $q$  represents the heat flux ( $\text{W/m}^2$ ) to the surface,  $k\rho c$  represents the thermal capacity of skin up to 0.1mm of 1.05W/m.k and  $t$  represents time.

The time to incapacitation due to radiant heat was calculated by Purser as

$$t_{Irad} = \frac{80}{q^{1.33}} \tag{9}$$

where  $t_{Irad}$  is measured in seconds.

The effect of conducted heat is directly related to the thermal inertia and temperature of the object, and the temperature of the interface between the occupant skin surface and the object (see Table 2-14 for examples of the different interface temperatures provided by materials).

**TABLE 2-14:CONTACT TEMPERATURES BETWEEN SKIN AT 35°C AND HOT BODIES AT 100°C[134].**

Material of the hot body	Contact Temperature(°C)
Mild Steel	98
Glass	82
Wood	65
Cork	46

In considering the effect of convective heat, the ventilation, humidity, the level of occupant sweat and the clothing of the occupant should be considered. If the value of 120°C is used as the likely temperature at which skin burns occur, and then averaging between the expected incapacitation of an occupant in humid or dry air the following formula was produced by Purser [113] to represent the time to incapacitation

$$t_{Iconv} = 5 * 10^7 * T^{-3.4} \tag{10}$$

This might then be expressed as a fractional incapacitating dose of heat per minute [113]

$$FED_h = \sum_{t_1}^{t_2} (\frac{1}{t_{Irad}} + \frac{1}{t_{Iconv}}) \Delta t \tag{11}$$

The limiting conditions of radiative and convective heat transfer are provided in. This data demonstrates the small tolerance times for relatively mild conditions. Obviously this tolerance is reduced when the effects are combined.

TABLE 2-15:LIMITING CONDITIONS FOR TENABILITY CAUSED BY HEAT [113]

Mode of heat transfer	Intensity	Tolerance time
Radiation	<2.5 kW.m <sup>-2</sup>	>5 min
	2.5 kW.m <sup>-2</sup>	30 sec
	10 kW.m <sup>-2</sup>	4 sec
Convection	<60° 100% saturated	>30 min
	100 °C <10%H <sub>2</sub> O*	12 min
	120°C <10%H <sub>2</sub> O	7 min
	140°C <10%H <sub>2</sub> O	4 min
	160°C <10%H <sub>2</sub> O	2 min
	180°C <10%H <sub>2</sub> O	1 min
*v/v		

In Pursers model the FIH acquired each minute is based on data using subjects with exposed skin, whereas in the Speitel model the FIH calculation is based on data using clothed subjects, and therefore produces a different formula;

$$FIH = t * 2.4 * 10^{-09} * (T)^{3.61}$$

(12)

The Purser model predicts incapacitation at significantly lower temperatures than the Speitel model. For example, using the Purser equation, one-minute exposure to 190°C results in incapacitation whereas temperatures in excess of 240°C are required to produce the same result within the Speitel model. The differences are due to the nature of the data used for the correlation.

A possible deficiency in both models concerns the exclusion of the thermal effects due to humid rather than dry air. The incapacitating effects of air with a high water vapour content are more severe than dry air as it reduces heat loss through sweat and delivers more heat to exposed skin [108-109,112-113].

The final major influence of temperature exposure is the damage that this may cause to the respiratory tract. Due to the nature of this injury, it obviously never occurs in isolation, but will always be accompanied by burns to the mouth and face. This type of injury is particularly dependent upon the humidity of the atmosphere. Dry air at 300°C causes burns to the larynx after only a few minutes, whereas at 120°C more extensive exposure would be required to cause burns, although pain would be experienced. In humid conditions, extensive burns to the respiratory tract may be caused at 100°C.

Apart from these more obvious forms of occupant injury, secondary injuries may occur after the initial ones. A psychological shock [108-109,112-113] may follow the severe pain

of heat exposure, as well as the partial/total loss of the use of the area affected by the burn. For particularly severe burns, a significant amount of body fluid may be lost into the burn area, resulting in possible circulatory failure and a fall in blood pressure with all of the accompanying side effects. Obviously the seriousness of these effects will depend upon the site and location of the exposed area.

Other factors that influence the effect of the exposure relates to the age of the occupant involved. In relation to the exposure of naked skin to high temperatures, the age of the occupant can have an important effect such that

- in general if 35% of body surface area is burned chances of survival are ‘low’
- if the occupant is a young adult, he has a 50% chance of surviving 50% burns
- if the occupant is young/elderly he has a 50% chance of surviving 20% burns[108-109,112-113].

As with the effects of irritant and narcotic gases, the effect of heat is dependent on a number of individual attributes. As such, it provides a general measure of the population reaction to the temperature of the environment, and will not be reliant upon individual sensitivity to the environment, which would be difficult if not impossible to model.

This section has highlighted interaction between the occupants and the environment. The decision process which an occupant employs when faced by smoke/heat/toxins, is not simply based upon the apparent smoke density, but will also be influenced by a number of other considerations. The process of moving through smoke will exert both physiological and psychological influences on an exposed individual. The psychological distress caused by the smoke manifests itself in an increased sense of anxiety that appears to rise while still enveloped. The physiological influence is dependent upon a complex interaction between the occupant, the smoke, heat and a number of other toxins. The physiological decline of the occupant is important, as it affects their mobility and velocity, possibly preventing certain activities involved in evacuations.

Purser examined the impact of the irritant and narcotic effects upon an occupant in relation to small furniture fire. From Figure 2-8 it can be seen that after the second minute, that the obscuration effect of the smoke would have prevented unobstructed escape. After 3 minutes the impact of the heat upon the occupant rises to an  $FED_{\text{heat}}$  of



over 2, denoting that the occupant would be subject to skin burns. Most dangerously of all, the FED of the asphyxiant gases rises to 5.0 after the fourth minute, denoting expected unconsciousness for anyone subject to this environment and that they would die within 6 minutes of exposure. Obviously this is only a single example of a specific type of fire. However, it demonstrates that the occupant will be subject to a variety of different influences during the incident, according to the stage of the fire.

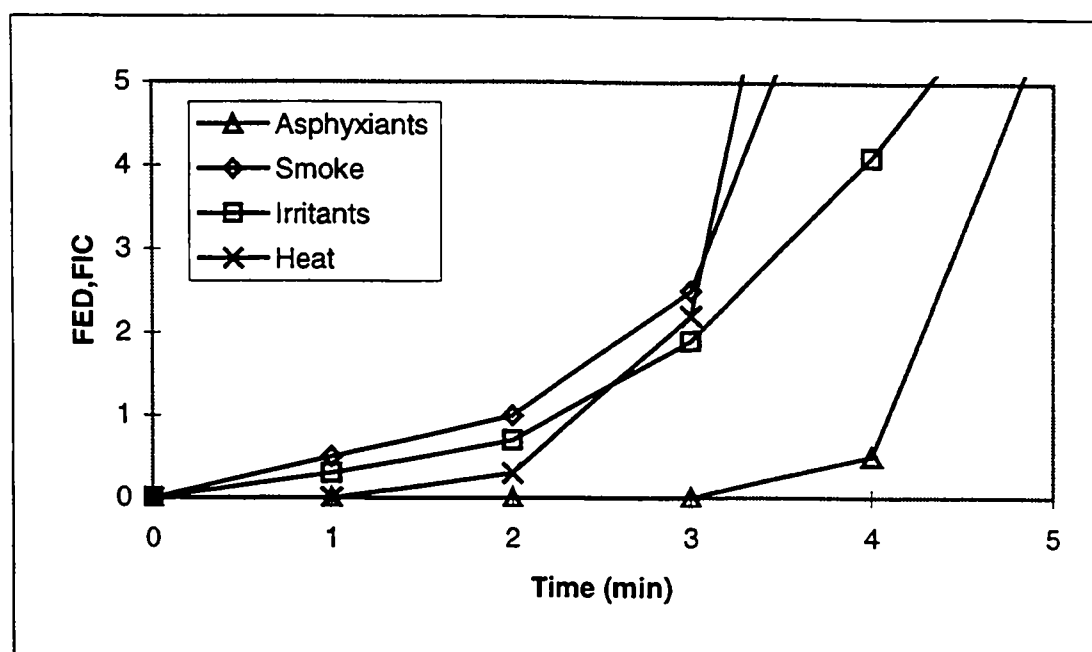


FIGURE 2-8: HAZARD ANALYSIS FOR A FURNITURE FIRE [113]

It is important to understand the effects of the environment upon occupants, with respect to individual occupant attributes. The manner in which the environment influences an occupant's condition will be dependent upon a number of the occupant's personal attributes, such as the gender, age and state of health. At present, the majority of evacuation models either ignore these considerations completely, or simulate this effect in a simplistic fashion [8]. However, even those models which do attempt to accurately reflect these factors [8], are somewhat restricted by the scarcity of data on this subject and the difficulty in isolating individual influences.

#### 2.6.4 INTERACTIVE BEHAVIOUR

*"A crowd is at the mercy of all exciting causes, and reflects their incessant variations. It is the slave of the impulses which it receives"*  
[74]

In the majority of cases, an individual is not isolated within a structure, but will interact with a number of other members of the population. This interaction, and the subsequent occupant actions, will be affected by the *relationship* between the individuals involved and their identities. These individuals may or may not be part of the same social/employment/familial structure, and this fact will influence the outcome of the interaction. This formation may be dependent upon a number of factors, as Brennan noted,

*“Various reasons for the forming of groups in threat situations prior to and during fight or flight behaviour have been suggested. They include information seeking, affiliation, formation of new norms in a situation where traditional norms are disrupted and social evaluation.” [107]*

If they are involved in such a social structure prior to the evacuation, it might encourage the recreation and maintenance of such a bond during an emergency situation. Sime [4] investigated such an activity and found that,

*“Individuals often move towards and with group members and maintain proximity as far as possible, with individuals to whom they have emotional ties.” [4] (see section 2.6.2.4)*

The type of social structures present will largely be determined by the type of enclosure in which the incident occurs (see section 2.6.2.3), and will be mirrored in the group formation during the evacuation. For instance, in dwellings, the occurrence of a *family* structure would be far more likely than in an office environment, whose group structures might be based more upon employment characteristics.

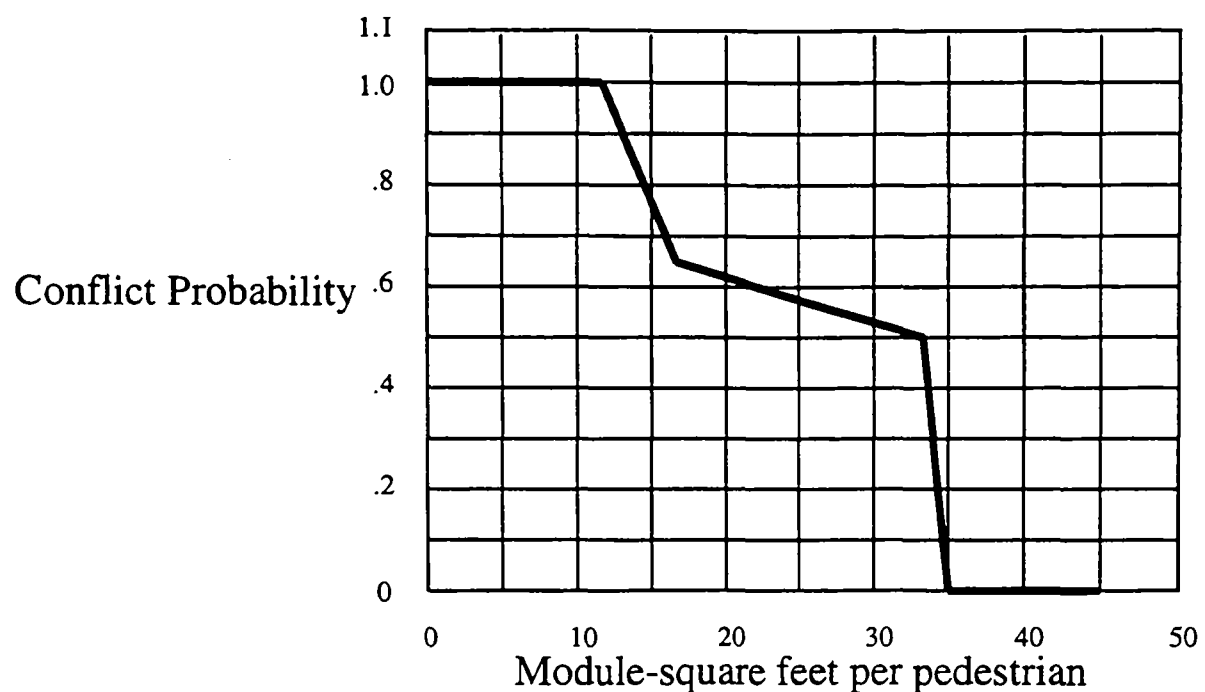
The level of interaction between the occupants was examined by Fruin [66]. He calculated the space required for occupants to manoeuvre comfortably within a crowd, allowing the avoidance of oncoming or crossing occupants. The existence of this space is fundamental to the ability of the occupant to avoid conflicts with other occupants (see Figure 2-9). Fruin defined conflict as

*“any stopping shuffling, or breaking of the normal walking pace, due to a too close confrontation with another pedestrian.” [66]*

Conflicts would therefore require adjustments in speed and direction. This definition does not include the social aspect of occupant conflict. However it might give an indication as to how often this event occurs.

The level of comfort implied by high population densities may also be significantly affected by the make-up of the population. Occupants might move or cope in a different manner if in a high-density familiar population, than if in an unfamiliar population.

These social groupings provide a framework within which individuals react, determining the initial level of co-operation between the members of the group, and the shape and size of the group, which will be drawn from the group configuration during non-evacuation activities.



**FIGURE 2-9: CROSS FLOW TRAFFIC PROBABILITY OF CONFLICT (REDRAWN FROM FRUIN[66]).**

The position of the occupant inside the social structure was observed as being critical to their activities during the event as,

*“Thinking and behaviour are a response to the social context as much as to the fire itself.” [135]*

In times of emergency people tend to adopt roles that are appropriate to one of these groupings [60]. This might entail a patriarchal family following the male head of the family, or several juniors following orders issued by their manager. As Lewis identifies,

*“Crowds have roles and norms.” [71]*

Wood supports this view, relating it to the domestic situation, such that,

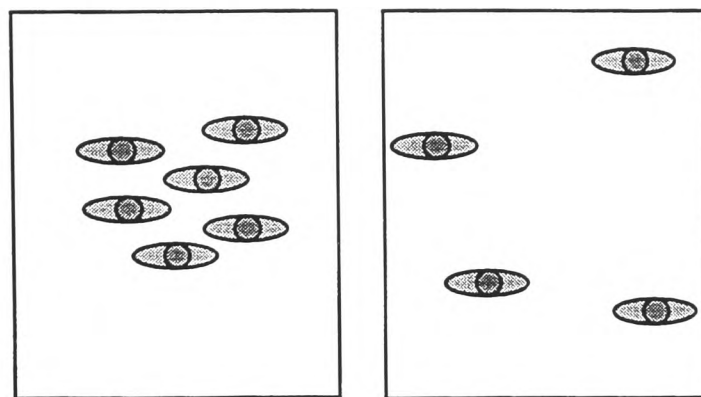
*“The apparent ease with which tasks are allocated and roles assumed in this situation is perhaps a function of the underlying hierarchical nature of family relationships, and is a reflection of the more formalised relationships of work.” [57]*

This group affiliation does not stop at a definition of role within the fire, but may in turn affect the immediate actions taken, so that a member of the group might perform a task expected of them in normal life; a father searching for their children, for instance.

Jones and Hewitt [58], examined 40 occupants evacuating from a 27 storey office. None of the fire management team was situated in the building, as if the event occurred on a Sunday. It was found that the leadership roles and the group formation were related to the formations seen in normal life and to those created in training procedures. This is an

important development as it might mean that intensive training could generate reciprocal group formations during an evacuation.

Once groups had been located or formed, the actions of the group, especially that of movement, tended to combine to produce an overriding single effect. For instance, the group, especially in circumstances involving emotional ties, tended to travel at the speed of their slowest member. Subsequently those responsible for making decisions within the group had to take this into account [61].



**FIGURE 2-10: COMPARISON BETWEEN TIGHT AND LOOSE DISPERSAL GROUP PATTERNS. THE TIGHT GROUP MIGHT BE AN EXAMPLE OF A FAMILY INCLUDING A SMALL CHILD, WHEREAS THE LOOSELY DISPERSED GROUP MIGHT BE MADE UP OF ADULTS.**

Proulx [80] identified this effect in her study of the evacuation of four apartment buildings, involving 150 people. Groups were seen to form within the population as they evacuated. Indeed 62% of the population, when questioned claimed to have formed a group, prior to evacuation. This high level of group formation might be linked to the enclosure being made up of apartments incorporating a number of family structures. Most of these groups were made up of 2-3 people. The dispersion of the group depended upon its population make-up (see Figure 2-10).

A family group involving a small child remained close together, possibly involving the small child being carried, whereas other groups, although maintaining their group structure, had a far greater dispersal. This make-up affected the group speed as,

*“The group formation likely delayed the speed of movement of the group, because members tended to assume the speed of the slowest person.” [80]*

The existence of convergence clusters has been observed even in unfamiliar situations. Groups of individuals gather in areas of agreed refuge and remain until it is safe to evacuate, or until assistance arrives. In the MGM Grand Hotel incident, guests gathered

in areas of environmental safety, and these groups were maintained until assistance arrived [136,137].

This can be compared to the results generated by Proulx and Fahy [106] in their survey of the New York Trade Centre evacuation, where clustering was seen on the 98th floor of the structure. However, these occupants were unsympathetic to the assistance provided, as it took *four hours* to arrive. This might highlight a general problem with restlessness in so-called 'safe' populations and the willingness exhibited by the occupants to remain within an endangered structure.

Collaborative groupings can therefore exist for a number of reasons: existing social structures, the ad hoc formation during the evacuation, gathering around an informed individual, or finally through the designation of a gathering point within which refuge can be sought, and greater communication between occupants is possible.

The benefits provided by such groups are dependent upon the surrounding population and the dimensions of the enclosure in which the event occurs.

Au et al [138] identified the occurrence of leadership in evacuations, and the effect of such individuals in the population. Their presence tended to attract other, less driven individuals, who might have been ill-informed concerning the incident, or less confident in their ability to escape. In such situations, ad hoc groups are formed as,

*"In an emergency, especially during the early stages, where people may be uncertain or confused, crowd behaviour can be strongly influenced by individuals who appear to be 'experts' or appear to know what to do."* [138]

This expert might be a manager, especially one who has had a large amount of contact with the staff, forming social bonds, or a predetermined warden issuing instructions [95] (see section 2.6.2.5). The activity of awaiting these instructions might have a negative effect, as these individuals might be unaware of the incident (a manager may be in a completely separate part of the building to the rest of the staff). Their delay in offering assistance may therefore prevent prompt action, by not communicating the correct evacuation procedure to the rest of the population.

A lack of trust by senior staff in their juniors may also cause a negative effect as seen at King's Cross where

*“At least 4 different groups of people investigated the fire in its early stages before giving instructions or taking actions to deal with the threat. These investigations happened, broadly, by junior people making an initial examination, calling on more senior people who investigated for themselves and so on. The time lost by these investigations almost certainly contributed to the eventual loss of life.”[97]*

‘Experts’, without any specific training or expertise may arise during an evacuation out of frustration with the fire staff available, or an acceptance of responsibility. Marrison and Muir made observations concerning egress behaviour and the effect of staff on such behaviour. They found that during evacuations involving non-assertive staff, individuals adopted the role of a staff member out of frustration at the inactivity of the present staff members[69].

Brennan [107,135] examined the breakdown of social hierarchies and the effect it might have on the evacuation. She found that the actions of junior members of staff were ignored by senior staff (in one case because they were in a meeting) who saw the alarm as inappropriate, delaying the evacuation of a number of occupants.

Lewis [71] claims that the role structure in the majority of crowds or groups can be divided into:

- the active core, who are protagonists, performing the group actions,
- the cheerleaders, who verbally support the protagonists,
- the observers, who do not take part, but remain nearby.

This work specifically dealt with crowd behaviour and the attempt of authority figures in controlling and manipulating such behaviour. The activities of crowd members could therefore be explained according to the role that they adopted within the crowd's social structure.

People are not indifferent to others, and will in general, attempt not to damage the chances of survival of other individuals, except at extreme levels of danger [52]. Instead they will attempt to communicate the possible existence of danger, or identify the best possible evacuation route [4]. *Generally, there exists a level of co-operative behaviour,*

up until a threshold, after which cues are perceived differently and danger is seen as almost unavoidable.

The local activities of individuals, who by acting co-operatively towards their own group, in slowing down or involving themselves in a specific action, can however be detrimental to the general population, by creating blockages, delays, or implying misleading evacuation plans. During her examination of high rise evacuations Proulx found that,

*“The groups with small children would have considerably slowed down the evacuation of other descending occupants, if there had been a crowd on the stairs.” [106]*

Collective behaviour can therefore have a *negative* local and global influence upon an evacuation. During the Marquee ShowBar (Summerland [53]) incident, the occurrence of death was almost exclusively isolated to those groups whose members were together when alerted. As the groups attempted to evacuate *en mass*, they moved too slowly to escape the danger [4]. Again, the group behaviour exhibited during the Summerland incident greatly increased the occupant crowding on one of the few available exit staircases, through the creation of a contra-flow system [53,54]. This was entirely due to the unusual situation where large numbers of parents were separated from their children. As the investigators reported,

*“The building and its use in occupancy as a leisure centre were novel and unusual and involved one factor which has not so far figured in any previous fire disaster. Parents tended to be separated from their children, since pursuits for each were located in different places- in some cases separated by three floors. When the fire was evident in the building, parents did not go directly to the exits...they naturally tried to find their children.” [53]*

MacLennan and Nelson [62] highlight the internal population of a group delaying response to an alarm system until it is clear that the group accepts the need to take emergency action. This behaviour is explained by Alexander et al [29], who claim that for every social setting, there exists a pattern of behaviour that conveys the best identity for that setting within the crowd. The individual wishes to conform to the group identity, which might be achieved by following others in the group and not evacuating. Latane and Darley [139] termed this inaction ‘*pluralistic ignorance*’, whereby group populations appear unconcerned, until the danger has been confirmed by a significant member of the group (a leader, manager, teacher), or where the responsibility to initiate response is

diffused amongst the population. This activity was seen as especially prevalent in populations where the incorrect assumption of danger would have involved a sanction, such as in adolescents [128].

*“Adolescents may be even more likely to look to peers for guidance on how to interpret a situation and even less willing than adults to initiate action that may lead to embarrassment (such as overreacting to cues).” [128]*

As previously stated, in normal or survivable conditions, it is possible for co-operative behaviour to develop between individuals who are not bound by emotional ties. Even under conditions that involve risk, the desire to evacuate tends not to overpower the social norms by which people live. This was evident in the severe conditions experienced at the Beverly Hills Supper Club incident and the Ohio concert incident [49,50,59].

A large number of altruistic acts were reported in the Beverly Hills Supper Club tragedy [49]. Their occurrence was most notable when the occupants began to pack around the only available exits, due to the extreme conditions that were evident in the rest of the structure. Even under these conditions, while the means to escape was apparent and close at hand, the occupant movement was orderly and constructive [49]. Under conditions of higher population density, at the Ohio Who concert [49,50,59], acts of altruism were responsible for saving lives; these acts were generally not based around familiarity. As one rescued patron commented,

*“Total strangers probably saved my life” [140]*

Mintz [141] identified behaviour as depending upon the perception of the reward structure. After defining a fire threat, a heterogeneous population perceives the reward structure as conducive to group/individual co-operative response. At an early stage, all of the occupants expect to be able to escape. Due to the individual location, the reward structure may change and initiate competition. At such a time an individual might feel that under co-operative behaviour, they may not reach an exit, and therefore may not reach safety. This perception may therefore determine the threshold at which the possibility of altruistic behaviour becomes dominated by competitive behaviour. This seems to fit the evidence provided by the Beverly Hills Supper Club where occupants maintained an altruistic outlook until the conditions were perceived as non-survivable, at which stage behaviour became more focused [52].



Muir et al [142,143] examined the extent to which individual behaviour changed (in respect to the surrounding populace) according to increased motivation to escape. This was achieved by conducting a number of aircraft evacuations (using groups of 60 passengers) in which the quickest evacuees received a financial reward. The evacuations were then repeated without the financial motivating factor, as a control, to simulate collaborative behaviour. The results, highlighted in Table 2-16, indicate a slight preponderance of men collecting monetary bonuses, possibly confirming the conjecture proposed earlier in section 3.6.6, that occupants adopt similar roles during an evacuation to those which they would expected to fulfil during their normal life.

**TABLE 2-16: ATTAINMENT OF BONUSES [142,143].**

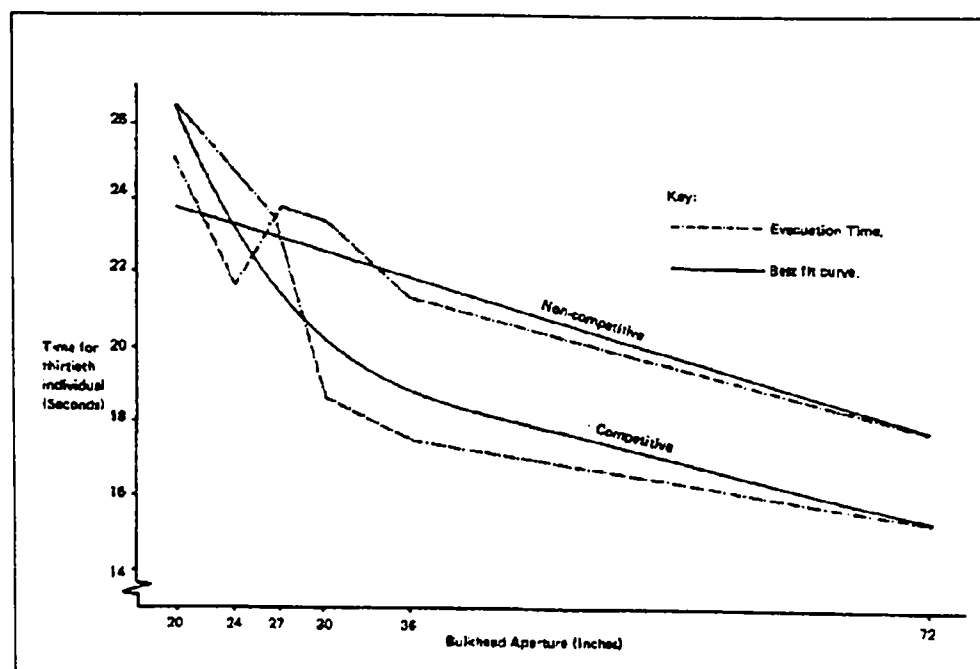
No of bonuses	% of volunteers	% of males	mean age(yrs)
0	12	57	29
1	17	67	30
2	37	74	29
3	25	77	28
4	9	82	27

Co-operative behaviour was far more significant when no staff/crew members were present to guide the occupants to safety. In such circumstances, a more orderly population flow enabled the population to move more quickly to the exits, decreasing the overall evacuation time.

In the co-operative evacuations, the differences between the times of the first thirty passengers to evacuate was not significant, indicating a steadier, less frantic evacuation. The behaviour in these evacuations was far less extreme than that witnessed in the competitive evacuations. Extreme behaviour in this situation would have consisted of climbing over seats, pushing and pulling other occupants, squeezing passed and climbing over other occupants, etc.

In the competitive evacuations, the effect of the bonus payments was to increase the motivation of the volunteers to evacuate faster. This desire did not guarantee faster evacuations, as blockages and struggling occurred due to the desire to get ahead of the other occupants. This was especially true when examining movement through small apertures as,

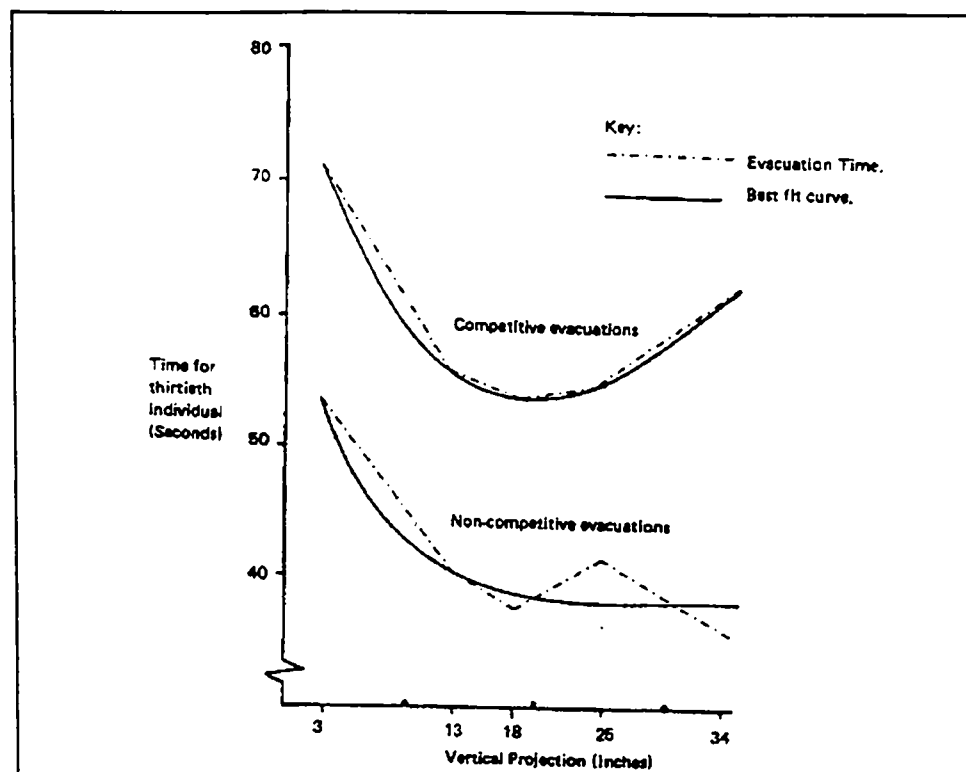
*“The smaller the aperture in the bulkhead, the more pronounced and more frequently the blockages seemed to occur. The blockages and people struggling against each other contributed to the slower evacuation times found in the results.”[ 142,143]*



**FIGURE 2-11: MEAN TIMES FOR COMPETITIVE AND NON-COMPETITIVE EVACUATIONS THROUGH THE BULKHEAD [142].**

In areas with greater access, the competitive populations were able to move more freely, causing less obstruction, and therefore decreasing the general evacuation time (see Figure 2-11). Muir et al [142] observed that competitive behaviour might actually slow evacuation times down, especially through small apertures (see Figure 2-12).

The results produced by these experiments should be examined carefully. Firstly it should be noted that they are *experimental* results, with the volunteers aware that no actual emergency existed. This may have inadvertently influenced the evacuee responses. Secondly, the assumption that the motivation to achieve economic rewards is equivalent to those that occur in achieving safety is *questionable*. Thirdly, the aviation environment is different from that of the built environment and may therefore elicit different behavioural reactions. Given these points of note, it should be recognised how difficult testing is in this area and that the experiment did produce some interesting and valuable results. Most importantly, Muir highlighted the possible disadvantages of unregulated competitive evacuation and that occupants cope with the surrounding environment (in this case unregulated flow) through adapting their behaviour accordingly.



**FIGURE 2-12: MEAN TIMES FOR COMPETITIVE AND NON-COMPETITIVE EVACUATIONS [THROUGH AN OVER-WING EXIT]. THE DIMINUTIVE SIZE OF THE APERTURE CAUSES BLOCKAGES/BOTTLENECKS WHEN COMPETITIVE EVACUATIONS OCCUR [142].**

The existence of interactive behaviour and group formation has a two-fold effect. Internally, occupant actions are defined in relation to the group structure in which they are situated. Externally, the effects of group behaviour can hinder the movement of the general population. Behaviour that would only be expected to exist only inside closely related groups, altruistic behaviour, can also exist between unfamiliar occupants as long as the motivation to be less collaborative is small enough. As summarised by Feinberg and Johnson,

*“The [occupant] response is neither instantaneous nor simply an aggregate of non-rational responses by individuals, as postulated by panic models. Rather, we argue that the collective response is social, is guided by normative expectations and role demands, and usually occurs only after information is sought and ambiguous cues are assessed.”*

[49]

There exist a number of individual traits that influence the egress behaviour of an occupant and therefore the behaviour of a wider population. These include the occupant’s age, gender, mobility, size, intellectual capability and their subsequent ability to perceive the events around them, etc. The proceeding sections will therefore concentrate upon the effect of these factors.

### 2.6.5 PERCEPTION AND RESPONSE

The perception of the danger itself is often identified as the most important factor in determining success in evacuation [4]. Obviously, a person cannot react to a danger they have yet to identify. The time to react to the perceived danger is seen as vital in

determining the success of escape, as crucial time might be lost in the misinterpretation of cues, which might lead to rash or desperate measures later. The effectiveness of alarm systems, fire wardens and enclosure usage, will have an effect on this perception, and therefore the reaction time of occupants.

This reception of information, in the form of environmental, social or physical cues, is not necessarily a passive act. Occupants may seek out information to increase their level of knowledge concerning the situation and therefore allow them to make an informed decision. This was highlighted by Tong and Canter who noted,

*“The discovery that people’s response in the early stages of a fire can be characterised as uncertainty reduction provides a firm base from which to refute the panic approach to evacuation as an instinctive response.” [82]*

Sime [4] identified the importance of the time people take to respond to information concerning the fire, and claimed that this was just as important as the actions after this response. He further suggested that these events did not occur in isolation of each other [4]. A delay in reaction may well prevent action options being available later on in the evacuation, as exit routes become unavailable, or incapacitation prevents a rescue attempt. This opinion contradicts the ‘ball-bearing’ theory of human reaction highlighted in Section 2.0. Melinek and Booth felt that

*“the difference between observed and predicted evacuation times...is probably due to the time taken to respond to the alarm and reach the staircase. People will often not respond initially to an emergency alarm. It is important to ensure that they do respond.”[144]*

Due to the complexity inherent in non-domestic structures, the cues that an individual might encounter are more ambiguous than in a domestic situation, where the individual will be far more familiar with the geography of the incident [65]. Obviously, in more familiar surroundings, unusual events and perceptions would be more apparent, as cues would be far more recognisable.

The more complex and unfamiliar the surroundings, both socially and physically, the more important the relaying of unambiguous, accurate information becomes, as an individual may be receiving information from a variety of sources that might include a number of different people, alarm systems, and their own perceptions [65].

As already identified in the Beverly Hills Supper Club and the Summerland tragedies, the complexity of the location and the lack of familiarity with the surroundings precluded earlier perception of the incident [52]. For the occupants to react to the incident it required them to come into contact with smoke or to receive information concerning the incident. *Even once this was the case, the ability of the evacuees to determine the safe evacuation time left was largely based on the distance that had to be covered to the available exits, rather than the exit conditions.* This was especially prevalent in the Beverly Hills Supper Club incident (as well as in the Valley Parade fire [145]) and contributed to the perception of the incident.

Donald and Canter [97] highlight the possibility that multiple cues might be necessary in unfamiliar circumstances to encourage a reaction. Furthermore, some cues will have more weight than others, depending on the situation in which they are received, the individual receiving them, and where the cue comes from;

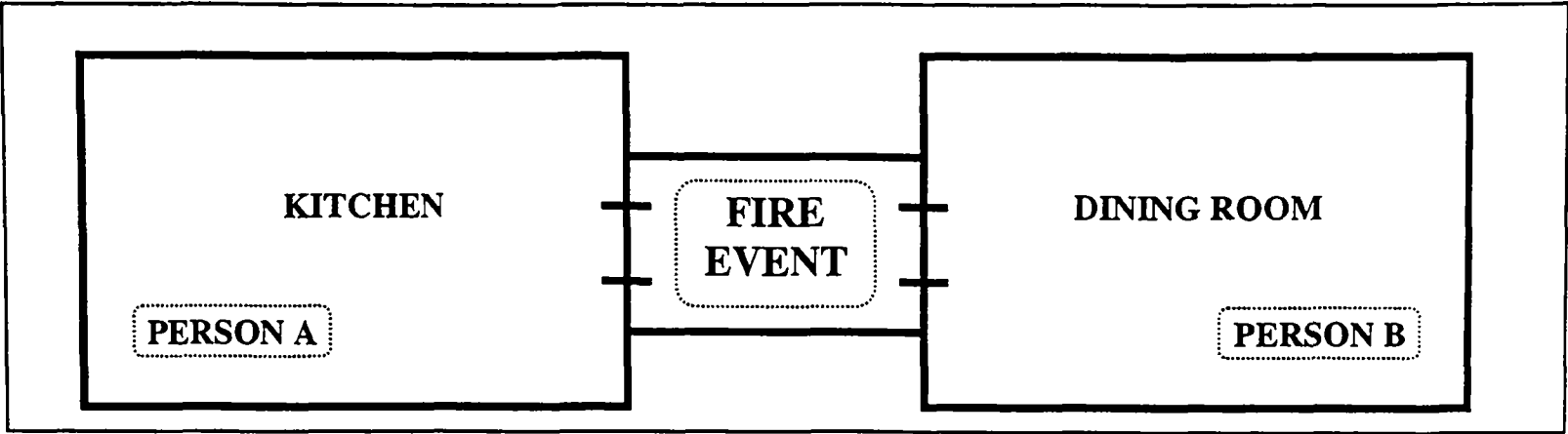
*“What is clear from the King’s Cross experience is that a number of cues need to be collected and noticed before action is taken. The only exception to this is when a policeman or similar figure gives an express instruction. Even when this is the case people may still seek extra information as to what is happening.” [97]*

The fact that these cues might not be simply additive but might combine in a more complex manner, is often overlooked to the extent that some existing models incorporate a system in which the accumulation of cues is assumed to be purely cumulative [36].

As well as the external identification of the structure, internally, certain areas will be designated for specific activities that may delay evacuation, or confuse the interpretation of cues (see Figure 2-13). During the Woolworth’s Department store fire in Manchester, many people delayed their evacuation, due to their proximity to the kitchen, and the belief that the situation was therefore not a serious one, as smoke was often seen to come from the kitchen [29,93]. This form of behavioural response was repeated in the Manila ‘Ozone Disco Pub’ fire of 1996 where occupant’s believed that the appearance of smoke was part of a special effects display, rather than the indication of an emergency. [146,147,148]

Therefore the position of an individual within a structure may not only determine the perception of certain cues, but whether these cues are interpreted as dangerous. This position may be determined by their pre-fire activity, such as a kitchen attendant, or a

particular interest in an area of the structure, such as a specific commodity in a supermarket, which might be located near to an incident.



**FIGURE 2-13: PERCEPTION OF AN EVENT. PERSON A, A KITCHEN WORKER, AND USED TO THE SMELL OF BURNING, MIGHT INTERPRET THE FIRE EVENT DIFFERENTLY FROM PERSON B, WHO IS AN UNFAMILIAR DINER.**

The occupant’s ability to perceive cues may be impaired through sensory disabilities (blindness, deafness, etc.). These disabilities may prevent early perception of cues, thus delaying the possibility of action. In extreme examples, most common in the elderly, sensory disabilities may go along with physical disability, causing a cumulative hindrance.

It might be expected that people with these disabilities would correct them through the use of devices, and that these may counteract many of the adverse effects. Proulx [80], in her study of an evacuation of an apartment block, found this not to be the case, to the extent that the disabled occupants did not evacuate unless they were directly told to do so, as the alarms were not audible. This had a positive effect in that the mobility impaired did not try to evacuate in isolation, causing evacuation difficulties (see section 2.6.6.3). However, those situated on the balconies of the apartments could not hear the fire-fighters knocking on the door, warning them of the incident.

It is important to understand the effects of personal abilities in the perception of cues, including visual, aural, and intellectual capabilities. It is often an oversight, that individuals may be categorised into discrete subgroups, such as disabled and able-bodied. A more accurate description might involve a continuous scale of abilities, augmented by an official labelling of occupants as disabled, which might entail an accompanying evacuation procedure.

Other factors may also be considered when examining the response of an individual to an event. In enclosures with formal evacuation procedures, the response times of

occupants may be pre-determined in the sense that they are following instructions to wait until the population density in a specific area has decreased sufficiently. Another consideration is the desire on the occupant's part to believe the cues that they are receiving. This may be due to there being considerable motivation for them to stay inside the enclosure. An example of this may occur if an occupant has purchased a number of goods, and evacuating would imply that they would have to relinquish these goods.

So far the assumption has been that the interpretation and reaction of occupants to cues occur in isolation of other occupants. However, as touched upon previously, the interpretation of cues is unlikely to be completely explained in isolation as Brennan identifies,

*“Fire cues which seem salient to observers may not be the most immediate cues for action. Many people will respond to them through a social filter. The interpersonal communication which occurs in fire situations is central to behaviour and an understanding of its operation is imperative.”[107]*

The divergence of activities is dependent upon a number of factors, especially the social structure in which the event occurs. When actions are decided upon, the physical capability of the individual to perform such activities will be a factor. This is especially the case in movement (examine Ando et al, section 2.6.6).

### **2.6.6 EXPECTED MOVEMENT**

Reliable information relating to flow rates for emergency movement during real-life evacuations is rare, due to the danger inherent in gathering such information. A rare example of such information, concerns the evacuation in 1911 of the Edinburgh Theatre, involving a population of 3000, which was timed at two and a half minutes, due in part to the bands ability to play the entire British national anthem, prior to evacuation [149].

In the light of the absence of reliable data, predictive methods are based on the observations made concerning estimated evacuation movement, simulated evacuations, or manipulations on regular individual movement rates. This draws into question the applicability of the data used in real emergencies.

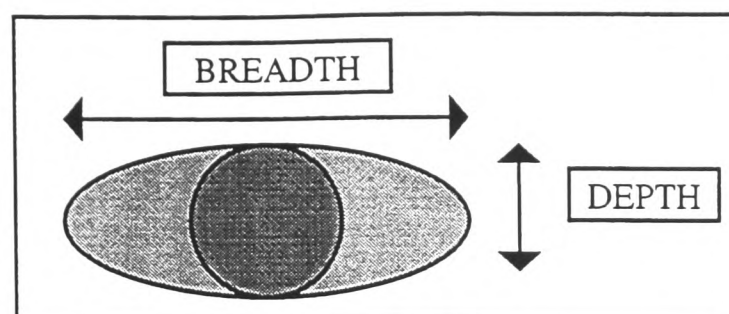


FIGURE 2-14: REPRESENTATION OF THE OCCUPANT DIMENSIONS

There exists a vast amount of work concerning the effect of the terrain on crowd movement and the flow rates of these crowds in context with the interaction between the population and the enclosure (an extensive examination of this work can be seen in Pauls' work [56]). This movement data concentrates on the speed (measured in the distance travelled over a time period), density (measured in the number of occupants per unit area), flow rates (measured in the number of occupants past a specified point, through a unit width), and size of the individual occupant (see Figure 2-14), and relates these factors according to formulae derived from a number of sources.

Pauls [56] identifies the difference between understanding the theoretical speeds that may be attained by individuals and the flow rates which might be achieved by specific populations, and the actual rates which are generated.

Pauls believed that to create an accurate picture of evacuation movement several factors needed to be considered:

1. *Flow times through flow elements, such as corridors and stairways.*
2. *The travel time for individuals to the most direct egress route.*
3. *Pre-movement times.*
4. *Time component due to behaviour that diverts the individual from the most direct path.*

The first two factors are related to the population flow times, and the optimal occupant egress routes, which he considered simple, physical calculations. In contrast, the remaining factors, were complex and involved social calculations. Pauls here makes the important observation *that evacuation movement has both a physical and a social aspect*, to its resolution. Much of the discussion in this section will concern the physical aspect of the occupant's movement.



### 2.6.6.1 HORIZONTAL MOVEMENT

A number of researchers have examined the impact of the population density and the dimensions of the enclosure upon the locomotive rates of individual occupants. What follows is a brief introduction to some of this work with reference to horizontal terrain. Much of the technical details concerning the contributions of Fruin [66], Pauls [56] and Predtechenskii and Milinskii [150] are incorporated into the work of MacLennan and Nelson [62]. Therefore, a brief examination of the work of these researchers will follow, augmented by several other works on occupant movement.

#### (i) Fruin [66]

Fruin's [66] work dealt with the flow of pedestrians, incorporating the size and shape of occupants' bodies, queuing in enclosures, and flow speed in relation to passage width, in estimating movement on stairways and across horizontal surfaces. A great deal of attention was given to the manner in which pedestrians maintained their speed and direction given the proximity of other pedestrians.

This information was combined to generate a '**level of service**' which described the relationship between the flow density and the speed of the crowd. The premise here being that as the population density increases (which he described in terms of 'Modules', in square feet per occupant), the ability to select locomotion speed decreases, and this is then reflected with a lower 'level of service'. As Fruin identified,

*"The Level of Service concept provides a useful model for the design of pedestrian spaces. Pedestrian service standards should be based on the freedom to select normal locomotion speeds, the ability to pass slow-moving pedestrians, and the relative ease of cross- and reverse-flow movement, at various pedestrian traffic concentrations."* [66]

He investigated the size of occupants, including factors such as clothing, and how this might affect the flow rates of the population. Occupants were not seen as responding to the environment uniformly, but were affected differently depending on the level of crowding.

The ability to move freely was calculated according to the area surrounding an individual, into which they could move, and the level of contact that this movement might cause. Zones were defined around occupants, identifying a 'touch zone' of 30 cm (12 inches) within which an occupant would expect to constantly come into contact with

other occupants, and a ‘no-touch zone’ of 46cm (18 inches), at which level this contact could be avoided.

Another important observation made by Fruin, was the existence of an ‘edge gap’, between the moving crowd and the enclosure, which was between 30–46cm (1–1.5 feet). This ‘edge gap’ might change depending on the purpose of the individual’s presence and the type of enclosure. For instance, Fruin suggested that window-shopping might require a greater distance gap, causing the occupants to generate an ‘edge gap’ of 0.9m (3 feet) [66].

TABLE 2-17:EXPECTED FLOW VELOCITIES FOR FLAT SURFACES[66].

FLAT SURFACES			
Level Of Service	Module Size in m <sup>2</sup> /per (ft <sup>2</sup> /per)	Avg. Flow Vel.in per/m/sec. (per/ft width of walkw./min.)	Comment
A	3.3- (35-)	0.4 (7)	Plaza
B	2.3-(25-)	0.5 (-10)	Station,small peaks
C	1.4- (15-)	-0.8 (-15)	Friction,heavy traffic
D	0.9- (10-)	-1.0 (-20)	Near critical
E	0.5- (5-)	-1.3 (-25)	Bulk arrivals
F	<0.5 (<5)	1.3+ (25+)	Extreme, contact.

The term, ‘levels of service’ provided designers with a scale from which they could determine the comfort of an individual occupant, in terms of freedom of movement, given the expected population density of the enclosure. These ‘levels of service’, in a scale measuring for A to F, concerning flat surfaces are given in Table 2-17.

(ii) *Predtechenskii and Milinskii [150]*

Predtechenskii and Milinskii [150] produced an influential work concerning merging population flows, taken from over 7000 observations. Their findings were based on utilising the flow/density graphs produced that were examined in relation to the number of people in the building and passageway widths. This consisted of calculating the population size in a specific area, and therefore the density, and deriving the speed and flow rate from this data. This took into account merging traffic flows, and the resulting changes in density and flow rate [150] (see Figure 2-15 and Figure 2-16).

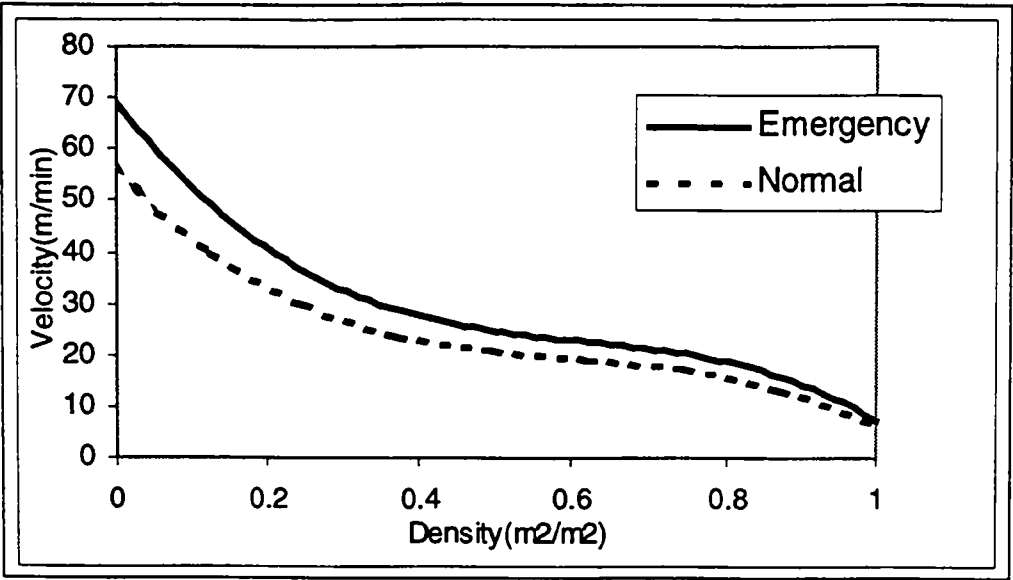


FIGURE 2-15: GRAPH OF THE RELATIONSHIP BETWEEN VELOCITY AND CROWD DENSITY (REDRAWN FROM PREDTECHENSKII AND MILINSKII) [150,151].

The equations used to generate this movement were:

$$Density, D = \frac{\sum f}{\delta * l} \text{ (m}^2\text{/m}^2\text{)} \tag{13}$$

$$(Traffic.Capacity), Q = D * v * \delta \text{ (m}^2\text{/min)} \tag{14}$$

$$(Flow.concentration) q = D * v \text{ (m/min)} \tag{15}$$

where  $\delta$  is the width of the passage stream(in m),  $l$ , the length of flow of people(in m),  $f$  is the projected area of ellipse of each person( $m^2$ ),  $v$  is the average velocity of the people in the flow (m/min),  $D$  is the density ( $m^2/m^2$ ),  $Q$  is the traffic capacity of the flow path ( $m^2/min$ ), and  $q$  is the flow concentration (m/min).

A significant difference between Predtechenskii and Milinskii and the other researchers, was their definition of density in terms of the area occupied by individuals, producing a density in  $m^2/m^2$ . This is important as it allows the model to take account of seasonal variations in body ellipse size, and different forms of encumbrance. As this was fundamental to their study, they required accurate body ellipse data. This ellipse size was calculated using the following equation,

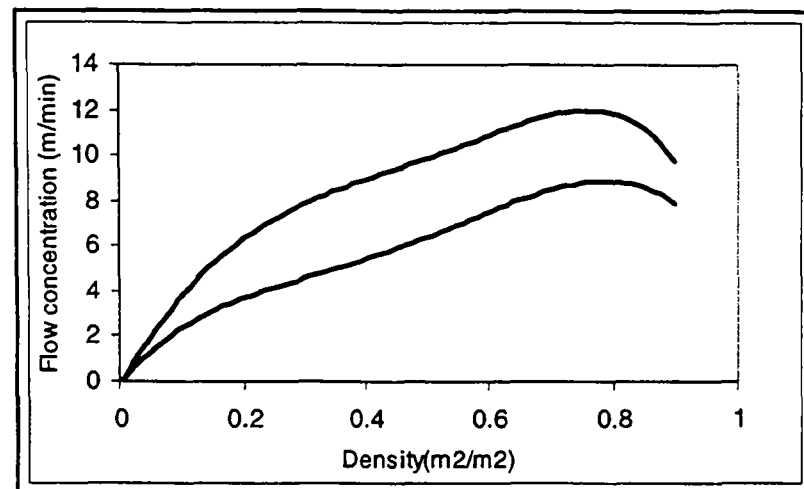
$$f = \frac{\pi}{4} * a * c \tag{16}$$

where  $a$  is the body breadth, and  $c$  is the body depth. The projected areas for the ellipse are shown in Table 2-18.

TABLE 2-18: PERSON SIZE DATA[151]

Person Type	Horizontal Projection (m <sup>2</sup> )	Shoulder Breadth ‘a’(m)	Body Depth ‘c’(m)
Adult	0.1-0.125	0.46-0.5	0.28-0.32
Youth	0.07-0.09	0.38-0.43	0.22-0.27
Child	0.04-0.06	0.30-0.34	0.17-0.21
Encumbered Adult	0.24-0.83	0.5-1.1	0.4-0.8

Predtechenskii and Milinskii generated a maximum density of  $0.92 \text{ m}^2/\text{m}^2$  (92% of the floor space being occupied). At a density of  $0.75 \text{ m}^2/\text{m}^2$  a maximum flow of 1.14 persons/sec/m was achieved under normal conditions in mid-season dress. At a density of  $0.72 \text{ m}^2/\text{m}^2$  a maximum flow of 1.40 persons/sec/m was achieved under emergency conditions, involving the optimisation of the parameters (see Figure 2-16). Their calculations did not include an 'edge effect'.



**FIGURE 2-16: RELATIONSHIP BETWEEN CROWD FLOW AND DENSITY (RE-DRAWN FROM PREDTECHENSKII AND MILINSKII)[151].**

*(iii) MacLennan and Nelson [62]*

MacLennan and Nelson [62], derived a descriptive system of movement based on the work of Fruin [66], Predtechenskii and Milinskii [150], and Pauls [56]. Their work, as are all of these researchers, is based upon the assumption that the occupant speed is dependent upon the population density. In turn, the population flow will be affected by the density of the population, and the speed at which the population is travelling.

MacLennan and Nelson calculated a '*region of interest*' within population densities of  $0.54 \text{ persons/m}^2$  ( $\text{p/m}^2$ ) and  $3.8 \text{ p/m}^2$ . Below  $0.54 \text{ p/m}^2$ , individuals could maintain a locomotive speed of their choice, whereas above  $3.8 \text{ p/m}^2$ , little or no movement was possible. There tends to be far greater disagreement between the different researchers concerning high-density populations. This is because the situations are difficult to replicate safely, and a number of other variables can have a significant effect under these conditions, such as the occupant's expectation of such high densities and cultural influences [62].

Between the two limits, the locomotion speed was hindered by the presence of the other occupants, and required calculation, depending on the population density. This was achieved using the equation,

$$S = k(1 - aD) \tag{17}$$

where ‘S’ is occupant speed, and ‘D’ is the density in persons per unit area. ‘k’ and ‘a’ are dependent upon the units being used in the equation, with ‘k’ being set to ‘k<sub>1</sub>’ (see Table 2-19) and ‘a’ to 2.86, when speed is measured in feet/minute and density in persons/feet<sup>2</sup>, whilst ‘k’ is set to ‘k<sub>2</sub>’ and ‘a’ to 0.266 when speed is measured in m/s and density measured in persons/m<sup>2</sup>. This equation could then be used to identify the expected rates of movement for a population across the terrain types identified, during an evacuation.

**TABLE 2-19: DEFINITION OF CONSTANTS USED BY MACLENNAN AND NELSON [62] FOR DETERMINING LOCOMOTION, AND THE RESULTS GENERATED.**

CONSTANTS		k <sub>1</sub>	k <sub>2</sub>	Max Speed (ft/min)	Max Speed (m/sec)
Corridors/ Doorways/Ramps		275	1.4	235	1.2
Stairs					
Riser(inches)	Tread (inches)				
7.5	10	196	1.00	167	0.9
7	11	212	1.08	187	0.9
6.5	12	229	1.16	196	1.0
6	13	242	1.23	207	1.1

These figures represent an amalgamation and recalculation using standard units, from the work of Fruin [66], Pauls [56], and Predtechenskii and Milinskii [150]. In a similar manner, a calculation for the specific flow, F<sub>s</sub>, was generated by

$$F_s = SD \tag{18}$$

where D is the population density, and S is the speed of movement.

F<sub>s</sub> is expressed in terms of the flow of evacuating persons past a point in the exit route per unit of effective width, W<sub>e</sub>. This unit of effective width is in feet if k=k<sub>1</sub> in Table 2-19 or in metres, if k=k<sub>2</sub>.

*(iv)Ando et al[152]*

Ando et al [152] conducted research concerned with crowd movement in a common direction, through densely populated railway stations. They produced walking speeds which were dependent upon the crowd density in a similar fashion to Predtechenskii and

Milinskii [150]. They also produced data concerning the unimpeded locomotion, which is shown in Figure 2-17.

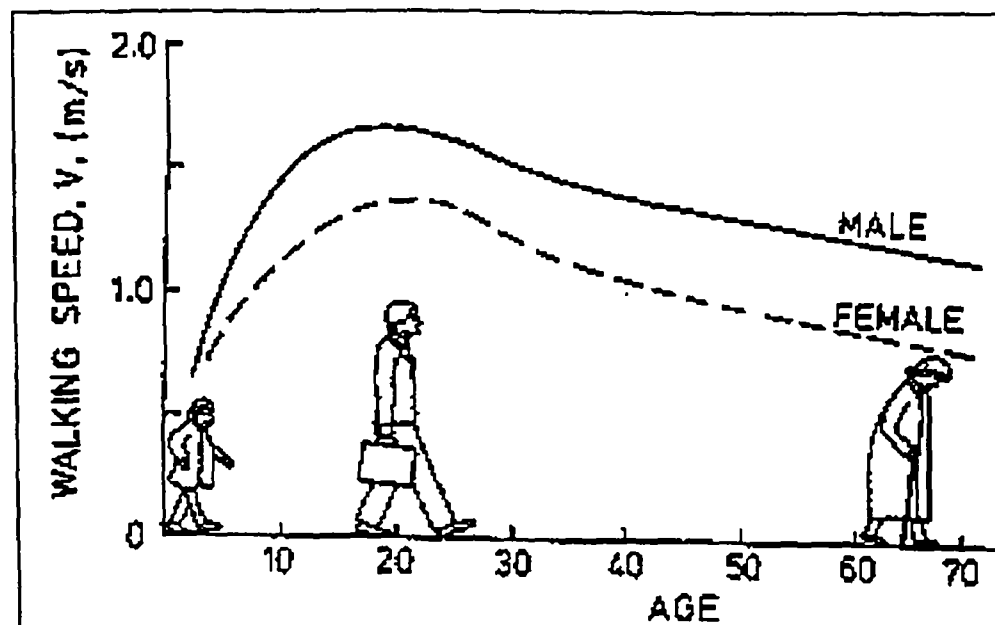


FIGURE 2-17: REDRAWN FOR THE ORIGINAL ANDO ET AL DIAGRAM. SPEED DEPENDENT UPON AGE AND GENDER [152].

They identified that the travel speed for males and females was age dependent and peaked at a common age of about 20 years. Furthermore, males were seen to outpace women at all ages, which may have been due to their longer stride pattern.

Ando et al noted that,

1. Under extreme conditions, that there existed densities of up to  $15 \text{ p/m}^2$ .
2. Stagnation was observed at  $4 \text{ p/m}^2$ , but restricted movement was also seen at this and much higher densities (see Figure 2-18).

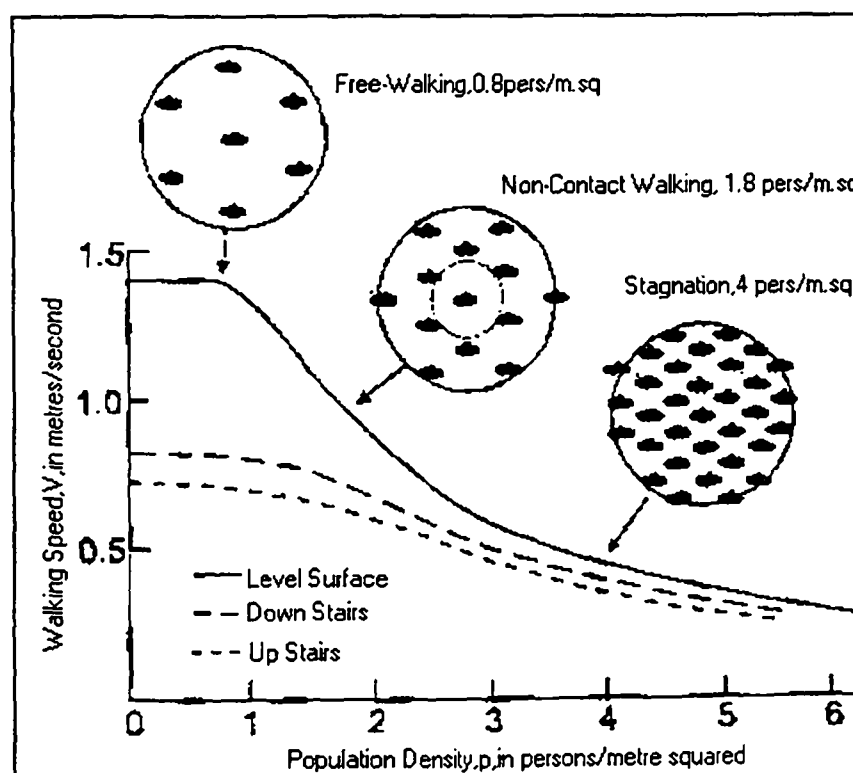


FIGURE 2-18: ACHIEVABLE WALKING SPEEDS GIVEN POPULATION DENSITY. REDRAWN FROM ORIGINAL DIAGRAM [151,152].

(v)Other Research Work

Smith [153] compiled a wide range of work including the work of Polus et al [154] and Older [155], as well as much of the work covered here. Polus et al examined pedestrian movement along Haifa sidewalks generating speeds of 1.3 and 0.7m/s at densities of 0.1 and 2.2 p/m<sup>2</sup> respectively. Population densities significantly greater than 2 p/m<sup>2</sup> were seen as rapidly approaching jamming conditions, and were highlighted as requiring further research. Older’s examination of pedestrian speeds in Oxford Street generated speeds of 1.4 and 0.3 m/s at free movement and a density of 4 p/m<sup>2</sup> respectively. These figures are included to represent the wide range of agreement visible in much of the work in this area.

A form of horizontal occupant movement that produces different movement rates to that identified above is movement through exits. This might be expected as the exit provides the target for many occupants’ travel, and also a narrowing of the width of floor-space. The unit flow rate for an exit is the measure of the number of occupants per metre of an exit width per second. The flow rate can then be found by multiplying the exit width by the unit flow rate of the exit. This assumes that a linear relationship exists between the exit width and the exit flow rate. According to literature [66,154,156], this assumption is valid with exit widths in excess of 1 metre, however there is some disagreement over the different gradients for this relationship (see Table 2-20).

TABLE 2-20: OCCUPANT UNIT FLOW RATE THROUGH EXTERNAL EXITS [66,154,156].

Source	The Unit Flow Rate (p/m/sec.)	
	Minimum flow	Maximum flow
Hankin[156]	1.46	1.46
Polus[154]	1.25	1.58
Fruin[66]	1.33	2.0

The flow capability of an external exit is dependent upon the exit type (standard, revolving, turnstile, free, swinging etc.). The exit unit flow rates defined in Table 2-20 refer to the standard exit type. Unfortunately, the current literature does not suggest different gradients for the different types of exit.

These flow rates were achieved at relatively low population densities. At higher densities not only is the likelihood of movement significantly reduced and the level of control over movement diminished [66] but the possibility of occupant injury is introduced. During

the Hillsborough disaster of 1989, densities of 10 p/m<sup>2</sup> were evident, presenting the potential for serious injury and death [63].

#### 2.6.6.2 STAIRWAY MOVEMENT

Movement upon stairways is more complex than that of horizontal surfaces due to the increased number of variables involved. The physical dimensions of the stairway have a significant effect upon the speeds attained by the occupants, far more so than would be the case in horizontal locomotion. The dimensions which will influence occupant speed include the angle of the stairway, the depth of tread, the riser heights and the presence and location of handrails. The restricted nature of the stairwell will also affect the movement of occupants, as the population densities change between the enclosure sections (between a room and a stairwell, for instance) causing bottlenecks and possible blockages.

Importantly, the direction in which the occupants are travelling will affect the speeds attained, involving an extra variable in our understanding of occupant movement. The direction of travel is important, especially when linked to the capabilities of individual occupants. All of these factors will assist/impede occupants in their movement.

##### *(i) Fruin [66]*

Fruin's examination of occupant locomotion included a detailed analysis of the movement of 700 people across stairways [66]. Unlike the previous investigation, his work considered the influence of the gender and age of the population, the angle of the stairs, and the riser height and tread depth.

His study involved the examination of occupant movement across an indoor stairwell (with 7 inch risers, 11.25 inch treads, implemented at an angle of 32°) and an outdoor stairwell (with 6 inch risers, 12.0 inch tread, implemented at an angle of 27°). A number of results were generated:

- on average the 27° stair produces faster speeds, indicating the influence of the stair gradient
- faster speeds (both up and down) occur for lower riser heights
- males are always faster than females.



**TABLE 2-21: STAIR TRAVEL SPEEDS AS DERIVED FROM FRUIN [66]. RESULTS ARE AVERAGES FOR TWO TYPES OF STAIRS AND REPRESENT SPEED ALONG GRADIENT.**

Gender	Age (years)	Down avg.(m/s)	Up avg. (m/s)
male	<30	1.0	0.7
female	<30	0.8	0.6
male	30-50	0.9	0.6
female	30-50	0.7	0.6
male	>50	0.7	0.5
female	>50	0.6	0.5

The results generated by Fruin, displayed in Table 2-21, are averaged to provide expected occupant speeds on stairways.

In a similar fashion to the results produced for horizontal movement, Fruin generated a ‘**level of service**’ which is applicable to stairwells. This assumes that the occupant locomotion will be dependent upon the population density, which are described in the form of ‘Modules’ (in square feet per occupant). The results generated were in terms of the achievable flow velocities.

Fruin’s work is important as it specifies a number of influences upon occupant behaviour, as well as producing a traditional flow expectation.

*(ii)Pauls [56,99]*

The idea of the ‘edge gap’ was further developed by Pauls [56,99], who incorporated it into his *effective width model*. He claimed that calculations based on the ‘unit width’ alone were inaccurate as people did not move shoulder to shoulder during evacuations, but maintain personal space in between themselves and other members of the population. (There are obvious similarities between this idea and the work of Fruin [66]). This principle was then extended to staircase movement.

The way in which the population uses a structure under normal conditions was highlighted as being of vital importance in understanding their behaviour during evacuations. Pauls did not expect people to instantly resort to using unfamiliar exits or move in a completely alien manner, and supported this claim by identifying that exit routes which carry high loads in normal use are the ones most used in evacuations (see section 2.6.2.4).

This empirically based description determines flow as a linear function of the stair's effective width, taking into account the propensity for occupants to sway, and the effect of the handrail.

He examined population flow rates on stairways during 29 drill evacuations of tall buildings, and calculated the 'edge effect' as being 0.3 metres. This generated the equation,

$$W_e = W_a - 0.3 \text{ (m)}, \quad (19)$$

where  $W_e$  represents the effective width, and  $W_a$  represents the actual width. This led to the stairway flow calculation of,

$$Flow = 0.206 * W_e * \left(\frac{P}{W_e}\right)^{0.27} \text{ (p/s)} \quad (20)$$

where  $P$  is the evacuation population. This flow calculation is derived from the effective width and the population size. Pauls also provided an equation for the flow rate derived from the population density that was,

$$Flow = 1.26d - 0.33d^2, \text{ (p/s)} \quad (21)$$

where  $d$  represents population density. Both of these equations were derived from Pauls' examination of evacuations from tall office buildings [99]. From these examinations Pauls calculated that if the population density did not rise above 0.5 persons/metres<sup>2</sup> then a horizontal locomotion of 1.25 m/s could be achieved, and stairway locomotion of 1.1 m/s (equivalent to 0.8 m/s horizontal locomotion). Although these speeds were achievable, they were not optimal. Using the equations above Pauls calculated that the optimal density, speed, and flow rate are a density of 2.0 p/m<sup>2</sup>, a speed of 0.5 m/s along a stair slope and a flow of 1.18 p/m/s of effective stair width. If the density reached between 4 and 5 p/m<sup>2</sup> then little or no movement was possible. Pauls recognised that these densities, might change depending on social and cultural factors.

He highlighted the importance of architectural design in stairway population flow and generated these guidelines for stairway design (similar suggestions can be found in Fruin's work [66]).

1. Stairways should be readily seen.
2. Tread size should provide adequate footing
3. Position of handrail is effective for all individuals
4. Uniformity of stairwell design.

These suggestions would help ensure the safe transit of the population along stairways at moderate levels of congestion.

(iii)Maclennan and Nelson [62]

Maclennan and Nelson [62] extended their work to cover the movement of occupants upon stairways. Using the same equation as that highlighted in the previous section concerning horizontal movement,

$$S = k(1 - aD), \tag{22}$$

they are able to generate movement rates for occupants, according to the riser size implemented (see Table 2-19).

As with their work concerning horizontal movement, their results are generated from the work of Predtechenskii and Milinskii [150], Fruin [66] and Pauls [56].

From Table 2-19 the effect of the riser heights upon the occupant’s speeds attained are apparent, with the higher riser heights reducing the maximum speeds attained. This equation provides a general guide to the speeds generated, but does not account for the individual abilities of occupants.

(iv)Proulx [80]

Proulx [80], generated stair movement data, concerning 3 multiple occupancy buildings. She found that stairway movement involved a complex set of behaviours such that the,

*“speed of occupants on stairs includes the time taken to rest, to peek into the corridors or chat with neighbours.”[80]*

This confirms the assertion that Pauls made in Section 3.4, that terrain traversal is not simply a physical movement.

TABLE 2-22:PROULX STAIR TRAVERSAL INFORMATION[80].

Building	Mean Descend Time(sec.)	Avg. Horizontal Speed(m/s)
1	15.4	0.5
2	20.1	0.5
3	20.6	0.6

Her examination included the movement of encumbered occupants down stairways. These included those carrying children, whose speed fell between 0.22 and 0.79 m/s. Although these figures might seem quite high in comparison with the other data represented in this report (Maclennan and Nelson [62], for instance), the movement of these occupants was sporadic as,

*“It was observed, however, that these people had to take extra precautions while going down stairs.”[80]*

This movement might have been improved by the low densities of the evacuation, allowing free access to handrails. Children between the ages of 2 and 5 were not carried, but instead moved along staircases grasping the handrail above their heads, providing a possible obstacle to other occupants, and denying access to the handrail.

Small children were calculated to move at 0.45 m/s on average during stairwell movement, while those over the age of 65 moved at 0.43 m/s (slightly lower figures than those generated by Ando et al [152]).

### **2.6.6.3 DISABILITY/AGE/INDIVIDUAL ABILITIES**

The movement of a disabled person should not be considered simply as a slowed down version of an otherwise 'normal' evacuee. There exist different levels of disability, some which, to various degrees, affect movement and egress behaviour, while others may have a more subtle effect on the evacuation. Furthermore, in structures that cater for large numbers of people with disabilities (e.g. hospitals) pre-defined evacuation procedures have been developed to cope with the occupants' special requirements.

It should be remembered that the visually impaired have special difficulties in the wayfinding process and do not simply suffer from small-scale navigational problems. As concluded by Passini and Proulx,

*“Building use and safety of the visually impaired population tend to be associated with the need to prevent accidents caused by collision and falling. Less evident but just as real is physical and psychological safety that comes with efficient wayfinding, particularly in cases of emergency evacuations.”[157]*

During this process, signage might take the form of radiators, door-knobs or door frames, as they move along the side of the corridor [85]. This might not be such a factor in those structures specifically designed for the visually impaired. However, in a less specialised structure, greater complications might ensue.

*(i)Pauls [158]*

Pauls [158] identified, from a number of evacuations involving the disabled from multi-storey office buildings, that 3% of his population could not be expected to traverse

multiple flights. However, less than 1% of the population used sticks or aids, and therefore moved far more slowly.

(ii)Shields, Dunlop and Silcock [159]

In Northern Ireland 12% of the population claimed to have locomotion difficulties [159]. Although this figure might be higher than that of the rest of the United Kingdom, this does demonstrate that during an evacuation, a significant proportion of the population should be expected to have locomotion difficulties.

TABLE 2-23: MEAN SUGGESTED MOBILITY AND TRAVEL SPEED ATTRIBUTE VALUES FOR OCCUPANTS WITH MOVEMENT DISABILITIES [159].

Aid	Number of Subjects	Mean Travel Speed (m/s)	Mean Mobility
Elec. Wheelchair	2	0.9	0.7
Man. Wheelchair	12	0.7	0.6
Crutches	6	0.9	0.8
Walking Stick	33	0.8	0.7
Walking Frame	5	0.5	0.4
Rollator	5	0.6	0.5
No Aid	52	0.9	0.8
No disability	19	1.2	1.0

There are a variety of disabilities that affect occupant locomotion. These disabilities require a number of different aids that allow the occupants some locomotion. Shields et al [159] in their examination of such locomotion generated the expected movement rates for those disabled occupants using specific aids (see Table 2-23). They did this by carrying out several tests in a day-care-centre offering participants with a wide range of disabilities, severity of disability, gender and age. The participants were asked to walk unassisted along a horizontal route measuring 50m.

TABLE 2-24: STAIR MOVEMENT FOR OCCUPANTS WITH MOVEMENT DISABILITIES(BASED ON [159]).

Ascending Stairs				
movement aid	mean speed (m/s)	range (m/s)	subjects	mean mobility
crutches	0.2	0.1-0.3	2	0.3
walking stick	0.3	0.2-0.5	9	0.5
no aid	0.4	0.1-0.6	18	0.6
no disability	0.7	0.6-0.8	4	1.0
Descending Stairs				
movement aid	mean speed (m/s)	range (m/s)	subjects	mean mobility
crutches	0.2	-	1	0.3
walking stick	0.3	0.1-0.5	10	0.5
no aid	0.3	0.1-0.7	18	0.5
no disability	0.7	0.5-0.9	4	1.0

The mean mobility values in Table 2-23 refer to the unimpeded performance degradation. These values were determined by comparing the mean travel speed for the class of movement disability with the travel speed for the class without movement disability. As can be seen in Table 2-23, there exist differences between the travel speed and the mobility of occupants using distinct aids [159].

For people with movement disability, stairs pose a particular problem. People with specific movement aids, such as wheelchairs, cannot use stairs unaided. In their study of the locomotion of the disabled, Shields et al [159] also asked people with particular walking aids to ascend and descend stairs unassisted. The values in Table 2-24 refer to unimpeded performance degradation.

The mean stair speeds exhibited in Table 2-24 demonstrate the vast differences between able-bodied and disabled occupants, in their ability to traverse stairs.

*(iii)Proulx [80,160]*

Proulx [160] in her examination of households in Canada, found that of the 4.2 million disabled people in Canada, 93.7% were living in private households. Of all households, 20% had both able-bodied and disabled occupants. This would obviously imply a high degree of interaction between mobile and the immobile. It should be acknowledged that the description used to define individuals in this respect is purely administrative. This might ignore a number of subtle disabilities, or individuals with disabilities slightly below the threshold of the 'disabled'.

It should not be forgotten that in the significant proportion of cases, the *elderly* will suffer some form of disability, or mobility problem. Proulx found that, in 1992, 11.8% of the population were over the age of 65, with one third of these living in private accommodation. Proulx surmises that,

*“Most people with disabilities and elderly people are determined to stay by themselves and live as long as possible in standard types of housing. It is not surprising, then, that more and more standard residential occupants contain residents with mixed abilities.”[80]*

Proulx identified activities which she found to be specific to the evacuation of the elderly :

1. They usually travelled in groups of two or three. A common activity was to exit an apartment and discuss the evacuation, prior to leaving.
2. The elderly tended to converse along the way, instead of maintaining a continuous speed [80].

The problems that might be caused due to the presence of the disabled during an evacuation (such as blockage, difficulty of movement etc.), can be alleviated by both configurational design and procedural inclusion. As we saw earlier, it is the difference in abilities, especially movement speeds, that causes much of the congestion, and local manoeuvring in evacuations. It is often the case that in those structures that have occupants of mixed ability, that there will be procedures in place which will account for these disabilities.

*(iv) Hirschler and Christian [161]*

The effect of fire hazards such as narcotic or irritant gases, heat and smoke (see section 2.6.3) upon the population will differ depending upon the constitution of the individual (a fact also noted by Purser [113]). For those with an ailment/impairment, or respiratory problem, this may be of distinct detriment to their evacuation chances. Hirschler and Christian [161] found that two thirds of the elderly, who are particularly susceptible to such conditions, did not survive in the residential fires examined. Of these fatalities, smoke was responsible for twice the number of deaths as in other residential fires examined.

In those enclosures with a majority of disabled/elderly, it is important to take into account the need for assistance, staff preparation and the availability of movement appliances. This might entail the physical movement of an immobile occupant to a safe area or assisting a slower moving occupant to a safe area [162].

Under these circumstances, staff tended to perform their tasks even in situations of risk, possibly due to the responsibility, and incapacity of their patients under their care (see Section 2.6.2.5) [80,130].

*(v) Juliet [163]*

During incidents involving disabled people that have been studied, members of the able population also assisted in the evacuation of the disabled, although members of the

public might not have been appropriately trained. Juliet [163] interviewed 27 occupants of the World Trade Centre in response to the evacuation of 1993. 14 of those questioned had severe mobility problems: 3 had sight/hearing problems, 2 had cardiac problems that limited their movement, and 7 had respiratory problems. All of these conditions would have hindered the successful evacuation of an occupant. The average evacuation time of this population was 3.3 hours. Although this seems a high figure, it should be remembered that the Trade Centre had over 100,000 occupants, and was over 100 stories high [106]. Through the examination of these impaired occupants, the researchers concluded that

*"In the absence of communication by authorities they[the disabled] gladly accepted assistance from colleagues and even from complete strangers during the evacuation. Those caring groups of people who assisted the disabled protected their 'charges' until they were safely evacuating and moved away from the building." [106]*

This altruistic act [164,165] must have slowed down the able-bodied occupants, although probably prevented a blockage that may have hindered the other occupants.

The procedural implications upon the immobile are often overlooked. The mobility impaired who had been moved to a safe area, to await further assistance often have to suffer the deafening sound of the alarm for a significant amount of time, prior to their rescue [160]. The refuge supplied to the immobile is separated by fire-resistive constructions, which must be able to resist the fire hazard typically for at least 30 minutes [117]. This provides an indication as to the duration of the stress the immobile will be subjected to due to both the sound of the alarm and the psychological difficulties of remaining in close proximity to the fire.

It should be remembered that during the evacuation, there exists the possibility that initially able-bodied people become incapacitated, due to smoke inhalation, burns, crushing etc. (see section 2.6.3). It would be difficult to estimate the proportion of the population that succumbed to such effects, and still managed to exit, and the effects of such a group on the population. On the whole, the procedures in place will not account for these new immobile occupants (especially if those affected were expected to care for existing non-ambulatory occupants), who will then have to be catered for by other occupants (as seen in the New York Trade Centre evacuation [106]) or the emergency services.



In general, the difference between the able and impaired is not a discrete one. Occupants naturally have a distribution of abilities that generally are dependent on a number of factors such as age, gender, health, etc. Furthermore, the transition from able to disabled may occur (or at least to less-able) during the evacuation.

The area of occupant movement, is one of great complexity and one which is only briefly touched upon in this section (for a far more detailed examination see Pauls [56]). The reason behind this complexity, is that much of the work concerns non-evacuation movement, and must therefore be converted to account for such considerations. Some consideration should be given to expected mode of travel whilst traversing each form of terrain. For instance, on stairwells, the occupants may choose different movement speeds depending upon configurational considerations, such as the riser width and the position of handrails. Furthermore, their level of encumbrance may introduce more 'body-sway', effectively taking up more room, both slowing the occupant down and affecting those occupants behind him.

The significance of the less-able/disabled occupants upon an evacuation is related to several factors. In a number of situations, their ability to evacuate is supplemented with configurational and procedural aides. However, in situations where the disabled form the minority of the population, these aides may not be provided. It is under these conditions that the difficulties that less able occupants face will have most impact upon the overall evacuation. Given that the disabled minority would then be dependent upon assistance to evacuate, the reluctance/ enthusiasm of the general surrounding population to assist is essential in determining both the safety of the less able, and the possible avoidance of significant blockages and delays.

The data generated provides the boundaries and expectations of occupant movement, but as a number of the researchers point out, does not completely determine occupant movement.

For any evacuation model to accurately simulate the occupant behaviour, a comprehensive movement model is essential. This model should consider the effects of occupant size, gender, ability, as well as the effect of population density on individual locomotion. As well as this, the type of terrain across which the occupant is traversing

will have a significant influence upon the speed and manner in which the occupant moves.

2.6.7 GENDER

The influence of gender, as with all individual traits, cannot be considered in isolation from other factors. It should be seen in context with the social setting, and the cultural expectations within this setting. In situations where there exists a rigid employment hierarchy (such as a hospital), gender has less of an effect, as the individual tends to adhere to the hierarchical position instead of a position that is gender specific [60]. In contrast, in a domestic situation the gender dichotomy appears more apparent, as this form of hierarchy largely determines the role of the individual according to gender.

TABLE 2-25: AN EXTRACT FROM BRYAN’S U.S. STUDY OF RESIDENTIAL FIRES IDENTIFYING A CLEAR BEHAVIOURAL DIFFERENCE, WHICH SEEMED DEPENDENT UPON GENDER [60].

First Action	Male Percent	Female Percent
Notified Others	16.3	13.8
Searched For Fire	14.9	6.3
Called Fire Dept.	6.1	11.4
Left Building	4.2	10.4
Got Family	3.4	11.0
Fought Fire	5.8	3.8
Enter Building	2.3	0.9
Telephoned Others	0.8	1.6
Tried to Extinguish	1.9	0.6
Nothing	2.7	2.8
Went to Fire Alarm	1.1	1.9
Removed Fuel	1.1	2.2

A number of studies have pointed to the different responses that are expected from the two sexes, with men seemingly more action-orientated, whereas women tend to be safety orientated [57,59, 60]. This might lead men to immediately fight the fire with the nearest available equipment and thus minimising the risk of the situation, whereas women tend, especially in familiar company, to pass on information and maintain a passive role (See Table 2-25).

These indications are culturally determined; therefore the effect of gender upon occupant behaviour should be taken in context with the social structure in which it occurs. Again this behaviour is complex, as the sexes may react differently in each other’s company, from the manner in which they act in isolation (see section 2.6.4). For instance, a woman acting in a family context might act differently from a single woman, as she might have specific responsibilities pertaining to her children. As with the effects of the structure on the actions on an individual, gender might not introduce new activities, or preclude

others from an individual, but may distribute the probabilities of action in a different way.

Muir et al [142,143] investigated whether the effect of heightened occupant motivation led to quicker evacuation times. They simulated this motivation by supplying monetary bonuses to the fastest 75% of evacuees. They found that the gender of the occupants generated a significant difference in the bonuses received, with men receiving a higher level of bonuses (see Table 2-26).

TABLE 2-26: THE GENDER OF THE PARTICIPANTS ACHIEVING BONUS PAYMENTS[142,143].

Gender	Avg number of bonuses	S.D.
Male	1.6	0.5
Female	1.4	0.6

The sexual divergence was also noted by Horasen and Bruck [128] in their examination of the student population of a secondary school. Although there were other location specific influences, there seemed to be a dichotomy between the initial actions of the male and female students. Females were seen to be more likely to leave the building immediately’ or warn others, whereas male students were more likely to ‘find an extinguisher’.

This lead them to the conclusion that,

*"the authors believe that differential responses may be real gender related phenomena"[128]*

From the examination of occupant behaviour, it is possible to distinguish between those dynamic attributes which will be affected by the procedural, configurational and environmental influences identified, and the base attributes which the occupant brings to the event, and which remain constant. It is important to correctly identify into which of these categories specific attributes fall, and if considered dynamic, the rate and extent of the change.

The way in which the factors highlighted combine is a complex issue. Many of the factors have both a psychological and a physiological effect. For instance, an occupant’s gender will influence the psychological manner in which smoke is interpreted, but will also affect the way in which the smoke affects the movement rate. Also, it is not entirely clear how the collection of factors combine to influence individual actions. The movement through smoke is influenced by a number of attributes including gender, age, familiarity, building usage, etc. Each of these factors has an identifiable effect

individually, but their effect in combination is less obvious. Whether they are additive, multiplicative, or whether one factor dominates in each case is a subject for further research.

## 2.7 PROPOSED BEHAVIOURAL MODEL

The previous sections have highlighted a number of important factors and responses that require addressing in any comprehensive behavioural model. From an examination of the models developed by Wood, Bryan, Canter, Breaux, Proulx and Lerup, [57,60,65,80,87,92], as well as the behavioural factors highlighted in this chapter, it is possible to develop a generalised model of occupant behaviour. This includes a finite list of the behavioural actions and the influences that can be expected during the evacuation of an enclosure (see Figure 2-19). This, in conjunction with the variables identified in the previous sections, could be utilised to generate a general behavioural model. For implementation it is obvious that further investigation and sensitivity analysis is required to determine the impact of individual developments upon the overall model. However, the model described here can act as a blueprint, pointing to the areas that require development.

This behavioural model is divided into three distinct stages, reflecting occupant information levels and the resultant behavioural actions. At stage  $t_1$  the occupant possesses a number of base attributes that the occupant contributes to the evacuation (age, gender, etc.). These internal attributes exist prior to the incident, but may develop during the evacuation according to local conditions. Combined with these are the surrounding events/conditions in which the occupant finds themselves (location, building type, surrounding occupants, etc.). These factors relate to the influences that are evident prior to the occurrence of the event. These also exist prior to the event but are external to the occupant.

At stage  $t_2$  an external event is perceived that then provokes a response in the occupant. This response will be shaped by the environment, the effectiveness of the alarm/signage systems, the surrounding population as well as a number of other factors. The decision made at this stage is not only influenced by these conditions, but also by the pre-event conditions of stage  $t_1$ , such as the occupant gender, location, etc.

The choice of behavioural response made at stage  $t_3$  will be selected from a finite set of actions. Unlike many of the behavioural models (such as the Canter model [65]) a detailed account of the behavioural activities has not been presented. For instance, the activity of communication might imply a number of actions such as ‘warn other’, ‘raise alarm’, etc. *The actual activity is therefore dependent upon the context in which it was made.* Therefore, if the activity of communication was performed when adjacent to another occupant then it will be interpreted as ‘warn other’.

The generation of such behavioural activities may not be as complicated as it initially seems. The activities identified (fight fire, re-entry etc.) are all made up from identifiable ‘blocks’ of behaviour, including searching, waiting, moving, the sharing of some attribute (this would involve the sharing of information, if the occupant is communicating), and a number of others. These behaviours are observed within a number of the behavioural activities. For instance, searching would be seen in fire fighting (to locate the fire), rescuing (locating the recipient of the rescue), etc. Therefore individual behaviour may be constructed from these ‘blocks’, limiting the necessity for complex design (This idea is pursued in Chapter 11).

Each time an action is completed, the decision-making process returns to stage  $t_1$  to redefine the next action process, as a consequence of the previous completed action, as identified by Lerup et al [87]. A function could be designed to generate the possibilities of the occupant behaviours, such that these probabilities may be produced through an examination of the different stages, and the combination of events. For instance, the probability of an occupant fighting the fire will be determined by the occupant details, the pre-event factors, and the reaction of the individual to environmental/ social cues.

When producing a behavioural model, a decision must be reached early on in the design process, concerning whether the model simulates the evacuation process *generally* or whether it incorporates the variety of influences identified in this report, which are causal to occupant behaviour. The first approach might represent egress movement as a system wide process, without local detail or identifiable occupant behaviour. The latter, will have the ability to incorporate specific occupant actions, which could then be traced back to variables provided by the model.

Unfortunately, most of the existing evacuation models [8] exclude the majority of the factors examined, and provide no justification for this exclusion (this problem becomes more apparent in Chapter 3). It can only be assumed that this exclusion is due to the computational overheads that such an inclusion might introduce into a model, or the difficulty that such representation entails. Although for relatively old models, the absence of a behavioural model may have been due to the perceived lack of relevant data and the limitations of the technology available, these would certainly not have been valid reasons for the more recent models. If either of these is true, then the accuracy of these models must be questioned, in respect of individual occupant behaviour. Although these models might accurately represent the evacuation of the majority of occupants as they exit the enclosure, they cannot claim to model the *decision process* involved. It would therefore be impossible, for the occupants modelled in the simulation, to perform actions that are related to the time frame and the factors around them, as would be expected in a real-life evacuation scenario.

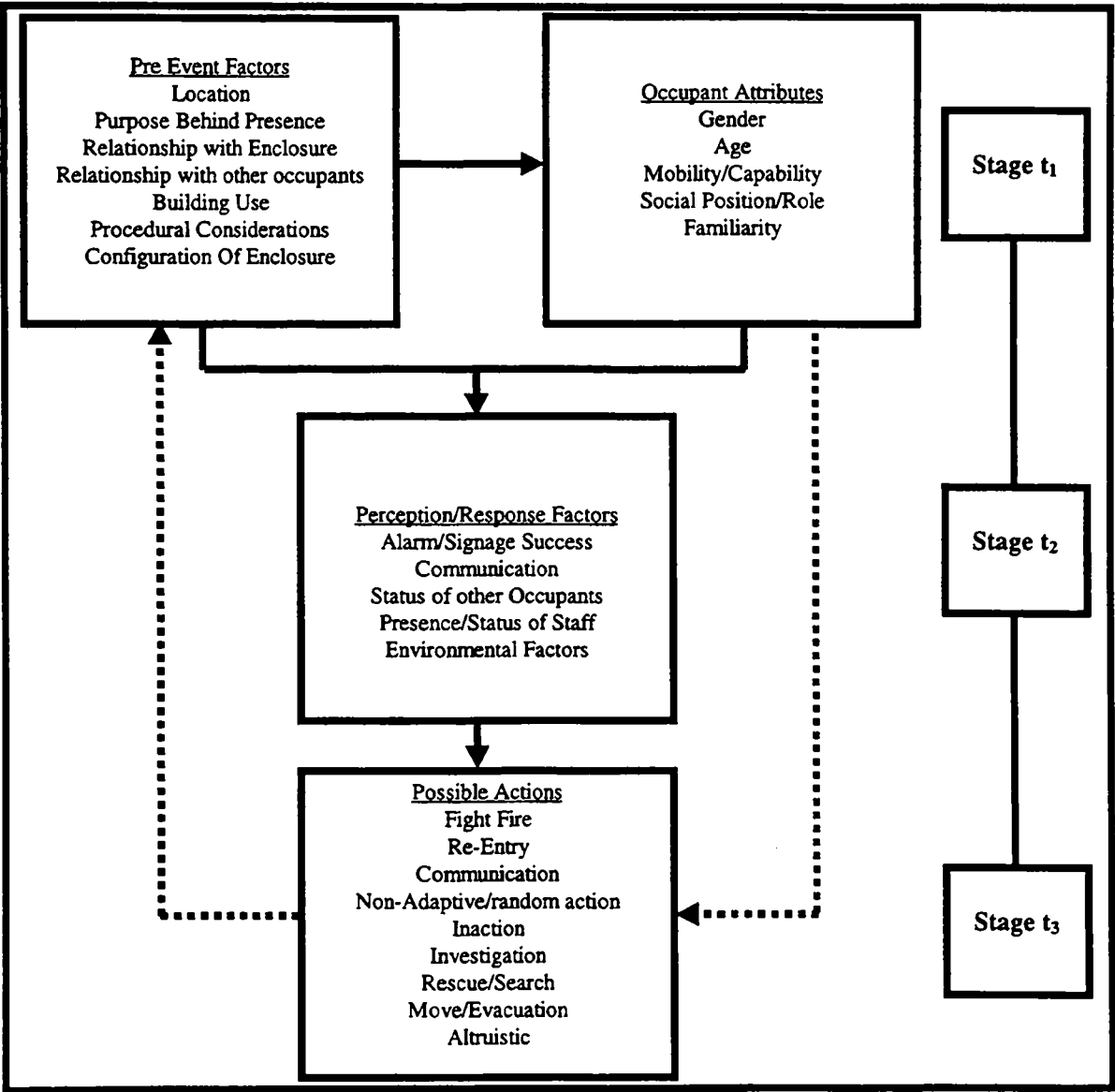


FIGURE 2-19:SUGGESTION FOR A BEHAVIOURAL MODEL, DEVELOPED FROM THE PREVIOUS ANALYSIS.

2.8 CONCLUDING REMARKS

Over the past four decades, the attempt at modelling evacuation has grown in sophistication. This has been due to a deeper understanding of occupant behaviour and,

with the advent and application of computer technology, to new methods of calculation. However, it is a simple task to produce what, on the surface, appears to be a sophisticated and comprehensive attempt at representing evacuation behaviour, whilst implementing simplistic procedures with inappropriate assumptions. The use of modern computer technology often confuses the user into mistakenly believing that the model is as complex as the system on which it is implemented.

The detailed review of egress behaviour reported in the literature presented in this chapter has highlighted a number of important points that should be considered in establishing an accurate picture of evacuation behaviour. The long-maintained belief, by some, that the majority of egress behaviour is panic-based has been questioned. The major influences upon evacuation performance were categorised into four areas: namely *configurational, procedural, environmental and behavioural*.

1) *Configurational* influences are based around the physical impact of the enclosure upon the evacuation of the occupants. This impact is generally shaped by the prescriptive regulations imposed at a national level, and will affect such considerations as the number and size of exits, and the maximum allowable travel distance.

2) *Procedural* influences reflect the pre-defined attempts to cope with the occurrence of an emergency, and the influence of the enclosure's use upon the evacuation. The effectiveness of the procedural implementations (e.g. alarm, signage, staffing systems, etc.), are all dependent upon the occupant's reaction to the information provided by these systems. The usage of the enclosure shapes the relationship of the occupant with both the enclosure and the other occupants. The enclosure, be it a hospital, a domestic environment or an office block, influences the role that the occupant maintains within the event, and therefore the actions which the occupant is likely to carry out.

3) The *Environment* influences both the physiological and psychological state of the occupants. This effect is due to the presence of smoke, heat, irritant and narcotic gases, all of which contribute to the egress behaviour of occupants, restricting their possible movement rates and influencing the egress path chosen.

4) Finally, the influence of an occupant's personal attributes and behavioural traits on the resulting evacuation performance was examined. These factors can be categorised into the following areas: *physical*, *psychological* and *sociological*. Physical factors include the attainable occupant movement rates across horizontal and inclined surfaces. Psychological factors involve the extent of the occupant's motivation to evacuate. Finally, sociological factors include the nature of the inter-relationship between individual occupants. It should be remembered that these influences would, in turn, be affected by the other three categories already identified. Although, the occupant brings a number of important behavioural considerations to the event, the manner in which these manifest themselves will be shaped by the other categories identified. For instance, the speed at which an occupant will be able to move will be dependent upon the occupants normal locomotion, but will also be affected by the effects of smoke inhalation, population density, the terrain, etc.

The description of occupant behaviour within this chapter has highlighted a number of factors that should be considered in the generation of a comprehensive evacuation model. For evacuation models to accurately represent such behaviour, they should consider the factors on which occupant decisions are based, rather than treating occupants as instinctive entities. At present, the number of models attempting to perform this task are limited indeed (such as EVACSIM and Firescap, see Chapter 3)[8].

Given that a number of behavioural factors have been highlighted as being essential to the simulation of evacuations, the ability of existing evacuation models to do so will now be examined. This will be done in Chapter 3, through determining the capabilities of the models as described by their creators. Due to the variety of methods used in representing the problems at hand, a scheme is devised to categorise the models, simplifying comparison and enabling a better understanding of the results produced.

The understanding of the behaviour that would be expected during an evacuation outlined in this chapter (see Figure 2-19) and the capabilities of the models currently available, will then provide a 'wish list' of behavioural developments that are required to make evacuation models more comprehensive in their representation.



**CHAPTER 3 CURRENT TECHNIQUES USED IN EVACUATION MODELLING**

The ethical and practical difficulties posed by the use of real occupants during evacuation trials were identified in Chapter 1, as were the limitations of formulaic means of assessing the safety of structures during an evacuation. Computer based evacuation models [14-50] offer the potential of overcoming the shortfalls of experimental or formulaic means of determining evacuation behaviour and address the needs not only of the designers but also the legislators in the emerging era of *performance* based building codes.

Research into quantifying and modelling human movement and behaviour has been underway for at least 30 years (see Chapter 2). This work has progressed down two routes, the first is concerned with the movement of people under normal *non-emergency* conditions. The second is concerned with the development of a capability to predict the movement of people under *emergency* conditions such as may result from the evacuation of a building subjected to a fire threat.

Some of the earliest work concerned with quantifying the movement of people under non-emergency conditions is that of Predtechenskii and Milinksii [150] and Fruin [66]. This research into movement capabilities of people in crowded areas and on stairs eventually led to the development of movement models such as PEDROUTE [39-41].

This work, although vital, is only a subset of what might be expected during an evacuation. It therefore represents a component of what is required for a complete evacuation model.

Evacuation research is somewhat more recent, one of the earliest published papers appeared in 1982 and concerns the modelling of emergency egress during fires [166]. Attempts to simulate evacuation essentially fall into two categories of model: those that only consider human *movement* and those which attempt to link movement with *behaviour*.

The first category of model concentrates solely on the carrying capacity of the structure and its various components. This type of model is often referred to as a “ball-bearing” model (also referred to as environmental determinism [4] ) as individuals are treated as unthinking objects which automatically respond to external stimuli. In such a model, people are assumed to evacuate the structure, immediately ceasing any other activity. Furthermore, the direction and speed of egress is determined by physical considerations only (e.g. population

densities, exit capacity, etc.). An extreme example of this type of model is one that ignores the population's individuality altogether and treats their egress en mass [45].

The second category of model takes into account not only the physical characteristics of the enclosure but treat the individual as an active agent taking into consideration their response to stimuli such as the various fire hazards and individual behaviour such as personal reaction times, exit preference etc. An example of this type of model is buildingEXODUS [5-7, 21-27]. These models require the type of analysis conducted in the previous chapter to reproduce appropriate occupant behaviour (although it is questionable as to how often this occurs).

The analysis performed during Chapter 2 has provided expectations of what is required in a comprehensive evacuation model. To represent the outcome of an evacuation accurately, the influences upon the model must not be limited to purely configurational factors but should also include the environmental, procedural and, perhaps most importantly, the behavioural influences.

A variety of different modelling methodologies are available by which to represent evacuation models. Within the modelling methodologies adopted, there are also a number of ways in which to represent the enclosure, population and the behaviour of the population. The myriad approaches that are available have led to the development of a variety of different evacuation models. To a certain extent the range of models reflects the purpose for which they were originally intended, the nature of the model developer (i.e. engineer/physical scientist/psychologist/architect) and the computer power available to the developers at the time of development. In the following sections an attempt is made to describe each of the modelling approaches and critically review the capabilities of each model in light of the approach taken. For a more detailed investigation into evacuation models, the reader is referred to the Society of Fire Protection Engineering Report that is based on this chapter [8].

A total of 20 evacuation models are described in this section. The models are subdivided into sections concerning their approach and level of sophistication. It should be made clear that the models are categorised rather than judged. It is not the purpose of this chapter to determine the quality of individual models. This would be inappropriate as the

models were created during different eras when vastly different levels of technology were available. Instead the models will be categorised according to the methods employed to replicate the outcome of an evacuation (in whatever form this might take). The accuracy of the individual models is reported according to the information provided by the designers. Any further judgement is left up to the reader.

Before examining the models in detail, each model will be outlined, identifying their common methods and major components. The discussion focuses on their purpose (see Section 3.01), the method used to represent the enclosure (see Section 3.02), the population perspective adopted (see Section 3.03) and the behavioural perspective used (see Section 3.04). This overview is followed by a detailed examination of each model (see Section 3.1-3.46).

To maximise clarity and brevity, the following key will be used throughout this section:

#### Models Currently Available:

BF= BFIRE [166]	E89=EXIT89 [34,35]
BG= BGRAF [14]	E= EXITT[36,37]
C= CRISPII [15,16]	F= FIRESCAP [49,50]
DE= DONEGAN'S ENTROPY MODEL[17]	MG= MAGNET MODEL [38]
EG= EGRESS [18-20]	O-O= OBJECT ORIENTED [168]
EXO= EXODUS[5-7,21-27]	PP= PAXPORT [39-41]
EP = E-SCAPE [29]	S= SIMULEX [42-44]
EV = EVACNET+ [30,31]	TF= TAKAHASHI'S MODEL [45]
ES= EVACSIM [32,33]	V= VEGAS[46-47]
EA= EVACSIM[167]	WO= WAYOUT [48]

The interrelationship between these various models is graphically illustrated in figure 3.1.

### 3.01 NATURE OF MODEL APPLICATION

While all the models under consideration address the common problems of evacuation, they tackle this problem in three fundamentally different manners: those of *optimisation*, *simulation*, and *risk assessment* (see Figure 3-1). The underlying principles related with each of these approaches influence the associated model capabilities.

Several of the models {EV[30,31],TF[45]} assume that the occupants evacuate in as efficient a manner as possible, ignoring peripheral and non-evacuation activities. The evacuation paths taken are considered as optimal, as are the flow characteristics of people and exits. These tend to be models that cater for a large number of people or that treat the occupants as a homogenous ensemble, therefore not recognising individual behaviour. These models are generally termed optimisation models.

Alternatively, designers may attempt to represent the behaviour and movement observed in evacuations, not only to achieve accurate results, but also to model the paths and decisions taken during an evacuation. These models { BF[166], BG[14], DE[17], E[36,37] , EA [167], EG[18-20] , EP[29] , ES[32-33], E89[34-35], EXO[5-7,21-27], F [49-50], MG[38], O-O [168], PP[39-41], S[43-44], V[46-47]} are termed simulation models. The behavioural sophistication employed by these models varies greatly, as does the accuracy of their results.

Several of the models do not attempt to determine the ‘egressibility’ of a structure, but are designed to cater for limited scenarios, dealing with specific circumstances. Risk assessment models{C[15-16], WO[48]} attempt to identify hazards associated with evacuation resulting from a fire or related incident and attempt to quantify risk. By performing many repeated runs, statistically significant variations associated with changes to the compartment designs or fire protection measures, can be assessed.

### 3.02 ENCLOSURE REPRESENTATION

In all models, the enclosure in which the evacuation takes place must be represented in some form. The assumption concerning the importance of the structure upon the success of the evacuation is universal. Two methods are usually used to represent the enclosure: fine and coarse networks (see Figure 3-1). In each case, space is discretised into sub-regions, and each sub-region is connected to its neighbours. The resolution of this subdivision distinguishes the two approaches.

In the fine network approaches {BF [166], BG[14], EG[18-20], EXO[5-7,21-27], F [49-50], MG[38], O-O [168], S[43-44] ,V[46-47]} the entire floor space of the enclosure is usually covered in a collection of tiles or nodes. The size and shape of a node varies from model to model, for example EXODUS[5-7,21-27] typically uses 0.5m x 0.5m square nodes, SIMULEX[43-44] now uses 0.2m x0.2m squares, while EGRESS[18-20] uses hexagonal nodes, of sufficient size to cater for a single occupant. The connectivity of the nodes also varies, in EXODUS [5-7,21-27] each node is connected to its 8 neighbours, in EGRESS[18-20] each node is connected to its 6 neighbours while SIMULEX[43-44] connects each node to a variable number of neighbouring nodes. Although the nodes may differ between different models, they tend to be uniform within each of the models, enabling a consistent representation of the geometric structure of the enclosure.

A large geometry may be made up of thousands of nodes and each compartment within the geometry, may be made up of many nodes. In this way, it is possible to accurately represent the geometry, and its internal obstacles, and accurately locate each individual at any time during the evacuation.

In the coarse network approach {C[15-16],DE[17] , E89[34-35] ,E[36-37], EA [167], EP[29] ,ES[32-33] , EV[30-31] ,PP[39-41] ,TF[45], WO[48] }, the geometry is defined in terms of partitions derived from the actual structure, which might include a corridor, a room etc. Thus each node may represent a room or corridor irrespective of its physical size. In this instance, the nodal mesh might be non-uniform. Nodes are connected by arcs that represent the actual connectivity within the structure. In such a model, occupants move from segment to segment, and their precise position is less defined than in the fine network models. An occupant might therefore move from room to room instead of from one area inside a room, to another. In some cases {E[36-37]}, the user may manipulate the model's representation so that coarse nodes may be combined to more complex occupant movement. However this is not their intended use and is, in effect, an attempt at remedying the shortcomings of the model through ingenuity of the user rather than by design.

This presents difficulties when incorporating local movement and navigation including overtaking, the resolution of local conflicts, and obstacle avoidance. This is because the exact location of an individual is not represented, and therefore detailed calculations of individual movement, and the interaction between individuals cannot be made. This limitation should be kept in mind when examining the behavioural models, especially those of EVACSIM[32-33] , CRISPII[15-16] and E-Scape [29] , whose designers claim have sophisticated behavioural models.

The difference between these two types of network model becomes increasingly indistinguishable when the evacuating population is treated as a homogenous ensemble (see Section 3.03).

### **3.03 POPULATION PERSPECTIVES**

The enclosure population, as with the geometry, can be represented in one of two approaches: an individual or global perspective (see Figure 3.1). Most models allow for

personal attributes to be assigned either by the user, or through a random device. These personal attributes are then used in the movement and the decision-making process of that individual. This process is typically independent of other occupants involved in the simulation, and allows for the individual trajectories/histories to be followed. The models that are based on this *individual perspective* {BF [166], BG[14] , C[15-16], E[36-37], EA [167], EG[18-20] , EP[29], ES[32-33], EXO[5-7,21-27], F [49-50] , MG[38], O-O [168] , S[43-44], V[46-47] } can then represent a diverse population, with different internal traits, whose evacuation, in some manner, relies on these traits. It is important here not to confuse independent decision-making with an inability to implement group behaviour. The definition of individual occupants does not preclude group behaviour, but examines each occupant individually, and then allocates an action, which might involve group behaviour.

Other models {DE[17], E89[34-35], EV[30-31], PP[39-41], TF[45] ,WO[48]} do not recognise the individual, but delineate a population as an homogenous ensemble (or a grouping), without separate, distinct identities, and therefore adopt a *global perspective*. These models represent evacuation details not on the basis of which individual escaped, but on the numbers of occupants who escaped. This approach may be beneficial in both the management and the speed of the models, but lacks much of the detail available to the individual perspective.

Whilst employing a global perspective, it would be difficult to model how events affect individual occupants (the effect of toxic fire gases, for instance). Only a distributed, or average effect could be established throughout the population. This would give no indication, for example, of the survival rates of specific groups of individuals, such as the elderly or the disabled, but instead, only that of the proportion of the population that had been affected.

This problem would arise for a number of other evacuation factors including any individual attribute, communication, the response of the individual to cues, and the interaction of an individual or subgroup with the rest of the population. This deficiency may not be considered serious in simple, homogenous populations, but in more realistic situations, where the population is more diverse, it would seriously hinder an accurate understanding of the behaviour of the population.

### 3.04 BEHAVIOURAL PERSPECTIVE

To represent the decision-making process employed by occupants in an evacuation, the model must involve an appropriate method in determining behaviour. Obviously, the behavioural perspective adopted will be influenced by the methods used to represent the population and the geometry, and as such is possibly the most complex of all the defining aspects.

Broadly speaking, the models investigated can be separated into the following five behavioural systems (see Figure 3.1):

No Behavioural Rules--{ EV[30-31] },  
 Functional Analogy Behaviour --{MG[38] ,TF[45] },  
 Implicit Behaviour--{ E89[34-35] ,PP[39-41], S[42-44],WO[48] }  
 Rule Based Behavioural System--{BF [166], BG[14],C[15-16],E[36-37], EA [167], EP[29],ES[32-33],EXO [5-7,21-27], F[49-50] }  
 Artificial Intelligence Based Behavioural System--{ DE[17], EG[18-20], O-O[168], V[46-47] }.

Models which apply *no behavioural rules* {EV[30-31]} rely completely on the physical movement of the population and the physical representation of the geometry, to influence and determine the occupant evacuation. In these models, decisions are made only on the basis of physical influences.

*Functional Analogy Behavioural* models {MG[38] ,TF[45] }, apply an equation, or set of equations, to the entire population, which then completely governs the population's response. Although it is possible for the population to be defined individually in these models, all the individuals will be effected in the same way by this function, and therefore will react in a deterministic manner to its influences, undermining individual behaviour. This function is not necessarily derived from real-life occupant behaviour, but might instead be taken from another field of study that is assumed to be analogous to human behaviour, (e.g. the functions that drive the Magnetic model were taken from Physics). Occupant movement and behaviour is then completely determined by this function, which may or may not have been previously calibrated with human movement.

Some models do not declare behavioural rules, but instead assume them to be *implicitly* represented through the use of complicated physical methods {E89[34-35],PP[39-41],S[42-44],WO[48]}. These models might be based on the application of secondary data, which incorporates psychological or sociological influences. For instance, the likelihood of performing a specific action may represent a variety of different influences, although are

not directly modelled. These models therefore rely upon the validity and accuracy of this secondary data.

Models which explicitly recognise the behavioural traits of individual occupants, usually apply a *rule-based system* {BF[166], BG[14],C[15-16],E[36-37], EA[167], EP[29], ES[32-33], EXO [5-7,21-27], F[49-50] }. This allows for decisions to be taken by occupants, according to pre-defined sets of rules. These rules can be triggered in specific circumstances, and in such circumstances, determine the occupant's behaviour. For instance, a rule may be:

***If I am in a smoke filled room, I will leave through the nearest available exit.***

Therefore in a particular set of circumstances, the occupant will perform a specific action. A problem with this style of decision-making process is that in simplistic methods {E[36-37] } the same decisions are taken under the same circumstances, in a deterministic fashion (as in the example above). This has the disadvantage of denying the possibility of natural variations in outcomes through repetition. Most of the rule based models {BG[14],C[15-16],EP[29],ES[32-33]} are stochastic. However others, such as buildingEXODUS {EXO[5-7,21-27] } incorporate the contribution of both deterministic and stochastic approaches, depending on the circumstances.

Recently, *artificial intelligence* has been applied to behavioural models {DE[17],EG[18-20], O-O[168], V[46-47]}, where individual occupants are designed to mimic human intelligence, or an approximation of it, in respect to the surrounding environment. These models attempt to generate occupant behaviour from a much lower level of representation, rather than imposing simplistic general modelling techniques upon occupant behaviour. Although this method has the capacity to more closely represent the occupant decision-making process, it has proved difficult to calibrate and even harder to validate.

The behaviour that can be expected in evacuations has a complex relationship with the surroundings. An individual may be broadly said to be involved in three types of interaction during an evacuation, all of which are associated with complex decisions. These encounters may be categorised as:

***People-People*** Interactions, i.e. interactions with other occupants.

***People-Structure*** Interactions, i.e. interactions with the enclosing structure.

***People-Environment*** Interactions, i.e. interactions with the fire effected atmosphere,



and possible debris.

These interactions will affect an occupants' movement (and general behaviour), and will therefore utilise the decision making process. This process is further complicated by the manner in which this interaction takes place. Again, this may broadly be said to occur on three levels:

***Psychological***-An interaction of this type under a fire threat might entail an occupant rearing away from the fire,

***Sociological***-An interaction of this type under a fire threat might cause an occupant to instigate a rescue of another occupant,

***Physiological***-An interaction of this type under a fire threat might result in intoxication due to narcotic fire gases.

As identified earlier, human behaviour is the most complex and difficult aspect of the evacuation process to simulate. No model to date fully addresses all the identified behavioural aspects of evacuation. However, several models have attempted to incorporate a number of these behavioural interactions. Furthermore, not all these behavioural aspects are fully understood, or quantified. As a guide to the capabilities of the various models and the methods that are implemented to address this problem, see Figure 3.1.

The purpose of this chapter is to determine the progress of evacuation modelling, highlighting any omissions that are evident within the existing models and gain an understanding of the methods used and the success at simulating occupant behaviour. Through this understanding the task of developing a behavioural model, that is attempted in Chapters 5-8, can be more clearly evaluated as well as providing a benchmark against which the proposed developments may be compared.

# EVACUATION MODELS

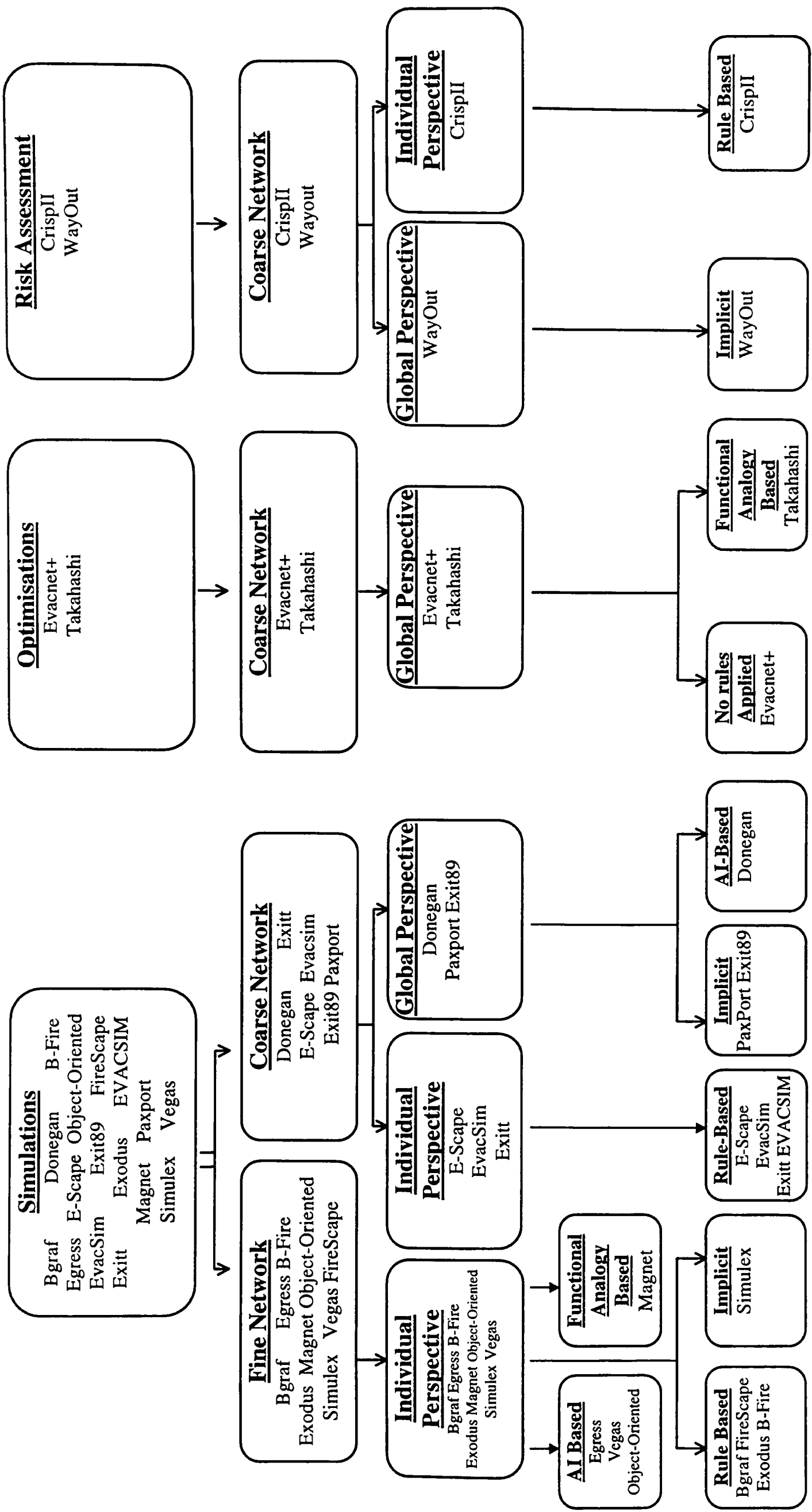


FIGURE 3-1:DIAGRAM REPRESENTING EVACUATION METHODOLOGIES.

### 3.1 SIMULATION MODELS { BG[14] , DE [17],E[36-37], EG[18-20], EP[29], ES[32-33], E89[34-35], EXO[5-7,21-27], MG[38] , PP[39-41], S[43-44], V[46-47] }

In this section the Simulation models will be discussed. The discussion is separated into Course Network models (Section 3.11) and Fine Network models (Section 3.12).

#### 3.11 COARSE NETWORK MODELS { DE[17] , E89[34-35], E[36-37], EP[29], ES[32-33], PP[39-41] }

The Coarse Network models are categorised according to the manner in which the population is specified, either using the a)Global perspective or b)the Individual perspective. The models are further subdivided according to the manner in which they include behaviour.

A)GLOBAL PERSPECTIVE{ DE[17] ,E89[34-35],PP[39-41] }

i)Artificial Intelligence Based Behavioural Models{ DE[17]}

#### Entropy As A Measure Of Structural Complexity

Donegan et al, developed an evacuation model for a multi-storey structure with a single exit based on a measure derived from Learning Theory. The model generates a statistic that is a measure of the relative complexity of the structure from an evacuation point of view. As such it is not an evacuation model in the traditional sense, however it can be used to investigate the relative complexity of buildings during an evacuation. As they commented,

*“The strength of challenge is related to the information which an occupant has in respect of available egress routes.” [17]*

Structures possess ‘latent complexity’ that is derivable from plans, through the use of an algorithm, making this method scenario independent. This complexity is due mainly to the number of options available to individuals who wish to leave via a recognised exit. The routes open to them provide the layout with an entropy (complexity) measure. The method used, based on Shannon Entropy [169], is designed to encompass egress uncertainty about the structure. This was represented by,

$$H(p(x)|x \in X) = -\sum p(x) \log_2 p(x), \quad (23)$$

where the summation is over  $x$ , and  $p(x)$  is a probability distribution on a finite set  $X$ .

The Shannon entropy is the summation represented above, given that  $\sum p(x)=1$ . The method analyses the structure through the use of topologically equivalent nodal networks, using the Concept Learning System. The main concept identified is,

*“Acquiring Knowledge with respect to Egress.” [17]*

Knowledge is gained from moving between nodes, except during backtracking. This is because all of the information gained is assumed to have been acquired during the first traversal. Indeed, by the time an occupant has evacuated, he is assumed to have traversed the entire network and to have calculated the most efficient exit route, such that

*"The complexity model ....presupposes that the evacuee has covered every path in the building before egress, i.e. on leaving, the evacuee has learned enough information to describe the building network."*[17]

In this way the model simulates the evacuation of occupants unfamiliar with the enclosure, an assumption vital to this model. The unfamiliar occupant is assumed, somewhat unrealistically, to have assimilated information concerning all possible exit routes, and then to make a judgement concerning the complexity of an escape route. This is made more feasible by the simplicity of the enclosures that are viable in this model.

The network may include the entire enclosure or a pre-defined smaller area. The probabilities of acquiring/not acquiring knowledge is,

$$p^+ = \frac{n^+}{n^+ + n^-} \quad p^- = \frac{n^-}{n^+ + n^-} \quad (24)$$

where  $n^+$  is gaining knowledge ( a positive instance), and  $n^-$  represents not gaining knowledge( a negative instance). Therefore the total entropy is,

$$H = -(p^+) \log_2 p^+ - (p^-) \log_2 p^- \quad (25)$$

The overall complexity for a given floor is taken as the *mean nodal complexity*. To generate this, certain assumptions are made, which include:

1. Evacuee has no previous knowledge.
2. No influence of other occupants.
3. All exits are equally likely to be chosen.
4. No signage exists.
5. Occupants experience no panic.
6. All occupants are able-bodied.
7. All networks are trees.
8. A back-track equals a positive and a negative instance.
9. Each evacuee has a path memory.

Many of these assumptions are contentious and inappropriate, for instance the lack of influence of other occupants, and all exits having the same probability of being chosen. It is not clear why these assumptions are necessary as the model developers chose not to explain their reasoning.

The model developers highlighted several areas for improvement including, the

introduction of stairwells, locked doors, the ability to cope with disabled occupants, occupancy weightings, the representation of signage and buildings with more than one exit.

The model possesses no hazard module, little occupant detail, and no group or sociological behaviour. There was no mention of the movement calculations involved in the model, or the details required to represent each occupant. The approach as outlined revolves around the decision-making process of the occupants, which is in turn only affected by the structural complexity.

The developers have attempted to compare their model with EVACNET+[30-31,169]. This comparison involved a multi-storey multi-exit structure. The developers found differences between the two sets of results, involving the identification of different optimal exits, and the effect on the results of the adding another exit. The comparison was made in terms of the information used by the Entropy model, and not, as might be expected, evacuation times, or fatalities. Finally, no information was provided by the developers concerning typical model run times.

### **EXIT89 [34-35]**

**EXIT89 [34-35]**, which was designed at the National Fire Protection Association in Massachusetts, is part of a suite of tools, used to simulate the movement of large numbers of people (up to 700 occupants), from high-rise buildings. EXIT89 is written in FORTRAN for large mainframe computers.

EXIT89 uses a coarse network description of the geometry and a global perception of the population. Up to 300 nodes can be used to form a network description of the enclosure. Over 100 10-second time intervals, the shortest route for each individual is calculated (that is to the nearest exit), who proceed along this route, until obstructed. The obstructions may be caused by environmental conditions. When this occurs, that node is removed as an option from the network, which might involve the removal of an entire room from the possible exit path. This implements the Hillier and Lieberman shortest route algorithm [170], in which people move to the closest exit from a local perspective, i.e. it may not be part of the quickest exit procedure.

The style of node used represents a structural component (a room, for instance), instead of a specified floor area. This component has an associated traversal time that is constant for all occupants. If an occupant is deemed to have waited for a long enough time, i.e. longer than the nodal wait time, then they are assumed to have moved to the next node. All occupants are assumed to have the same response time to the emergency, although this is not to be confused with the nodal wait time.

This movement is affected by an encumbrance factor, where individuals are slowed depending on what baggage they are carrying, clothes they are wearing, etc. This might be used to simulate an adult carrying a child, or transporting valuables, but it is not obvious whether this facility could be enabled during the simulation, as opposed to at the start of the simulation. This factor would also affect all of the occupants of a node, as the population is defined according to mean body dimensions. The user is only able to choose between which sets of data they choose, instead of identifying individual traits and dimensions.

EXIT89 can cope with the effect of toxicity, but this can only be applied post-simulation; thus these effects do not contribute to the evacuation performance. The only contribution of smoke to the model is therefore one of blockage, as the occupants cannot physically interact with the environment during the simulation. Any fatalities are calculated post-simulation.

It calculates movement according to the equations devised by Milinskii and Predtechenskii [150] (see Chapter 2), and does not account for individuals resorting to crawling, or reversing direction. Individual occupant speeds are not calculated, but instead, the average velocity of a nodal population is calculated depending on the population density of that node, and is given by,

$$\text{Corridor travel, } V = 112D^4 - 380D^3 + 434D^2 - 217D + 57 \text{ (metres/minute)} \quad (26)$$

$$\text{Movement through doors, } V_o = V(1.17 + 0.13(\sin(6.03D_o - 0.12))) \quad (27)$$

and

$$\text{Movement down stairways, } V_{\#} = V(0.775 + 0.44e^{(-0.39D_{\#})} * (\sin(5.15D_{\#} - 0.224))) \quad (28)$$

where  $V$  is the velocity, and  $D$  is the stream density. Variations on  $V$  and  $D$  are relative to horizontal movement, for instance  $V_{\#}$  is the velocity down a stairwell. The

recalculation of such an equation would be extremely time-consuming, therefore tables of velocities and densities were used, based on these equations.

EXIT89 is not capable of modelling local movement effects, such as jamming or shuffling, as crowd speed is calculated instead of individual occupant speed.

The queuing procedure is handled,

*“By the decreased walking speeds that result from increased densities as more occupants move into a room or stairway. The program does not currently allow occupants to select less crowded routes. They simply join the queue at nodes along the shortest route.”[34]*

The population therefore dumbly moves into queues, which may well have been avoided by reassessing the situation.

When EXITT[36-37] (see Section 3.11b)i)) was restructured as part of the EXIT89 development, many of the behavioural measures identified were switched off, or ignored due to the increased number of people being modelled.

An attempt was made by the developers at validating the model. This initially involved comparing the results of a fire drill involving 100 occupants in a nine-storey building, to model predictions(see Table 3-1).

TABLE 3-1:RESULTS OF VALIDATION [34]

	Actual Results	First Run	Second Run
Time	7 minutes	5.6 minutes	10 minutes

On the first simulation run, the 'emergency' movement equations were used (implying optimising the use of all of the variables involved in the movement equations, and therefore minimising the evacuation times), producing a discrepancy of 1.4 minutes; effectively, an error of 20%. The authors explained this discrepancy by identifying that the validation data was taken from a drill and may not have appropriately generated the conditions that warranted the 'emergency' movement equations. The simulation was then run again using the 'normal' velocity version of the Predtechenskii and Milinskii [150] equations, which overestimated the time by 3 minutes; an error of nearly 43%. The developers did not comment upon this result. No other information was provided concerning the status of the occupants, relating to the awareness of the upcoming drill. Neither of these attempts at validation is particularly convincing.

The developers highlight the need to include responsibility, as well as more comprehensive inclusion of individual capabilities, including differing response times. Recently [171], the ability to model occupant delay times has been introduced. However, this is location-based according to the starting node of the occupant and cannot be individually attributed. It is not clear exactly how this was achieved given that a global population perspective is used.

These should be joined by the enhancement of individual identities, so that the occupants are no longer attributed an average set of traits, but are distinct. Although individual occupants can be traced throughout the evacuation, these occupants have no identifying traits, and therefore make up an homogenous population.

Recent enhancements include the incorporation of familiarity, non-optimal route choices, and the simulation of disabled occupants through the implementation of slower movement rates [35]. The representation of disabled occupants is achieved through entering the proportion of expected occupant speeds achievable. This method of representing disabled occupants assumes that the reduction in occupant speed is the only impact that they have upon the able occupants [171].

TABLE 3-2: VALIDATION EVACUATION TIMES [171]		
	Actual Times (secs)	Simulated Times (secs)
Day time	44.9 [15.0-135.0]	45.3 [23.0-117.0]
Night time	47.0 [17.3-150.9]	47.2 [24.3-130.2]

Some validation was conducted to test this new feature. A series of evacuations were conducted to examine the impact of disabled occupants upon occupant flow. From Table 3-2 the quantitative results produced seem very encouraging although further analysis is required concerning the qualitative aspects of the evacuation as well as how sensitive the results are to fluctuations in the data-set.

II)IMPLICIT BEHAVIOURAL SYSTEMS{ PP[39-41] }

PEDROUTE/PAXPORT [39-41]

PedRoute and PaxPort are related products designed to model the capacity and flow of passengers through passenger terminals. PaxPort[39] has been developed by Halcrow Fox as a derivative of, and now incorporating PEDROUTE[40-41]. It was originally designed



as a DOS utility but has now been developed to be compatible with the Windows 3.1 and Windows 95 systems. It was designed in partnership with London Underground Limited to simulate the movement of pedestrians around large-scale transport facilities [172].

Terminals are modelled by implementing a coarse network around which large numbers of passengers move (up to 30,000), according to different flow rates and pre-defined delay points (see Figure 3-3). The system is able to import and utilise DXF files from CAD packages. This information can be used in creating the enclosure layout. The passengers are not modelled individually, but may arrive in one of 16 different group types (which are determined by the type of service the group requires, such as a domestic flight, long haul, short haul, etc.), each of which have particular characteristics. In this manner, a number of passengers can be modelled by defining them as a member of one of these groups. Group members adopt traits within a distribution of values, which are dependent upon the nature of the group. The passenger types require the user to supply several other pieces of data including,

- the arrival times
- the process a passenger is expected to follow
- the possibility of escorts
- the free time of the passenger
- the encumbrance levels
- the possibility of using certain facilities
- whether the passenger follows signage

These characteristics are then applied to large clusters of passengers, which might represent the arrival/departure of a specific flight.

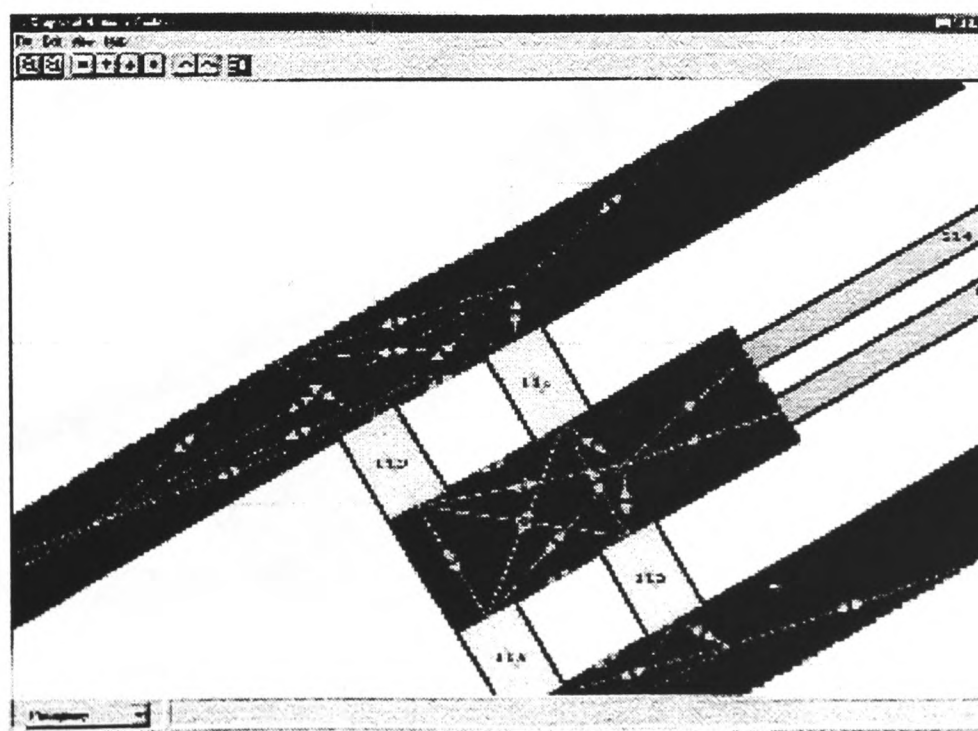


FIGURE 3-2: NETWORK BUILDER USED IN THE PEDROUTE SYSTEM[172].

The enclosure is made up from 'blocks' which can be chosen from:

- passageways,

- moving walkways,
- stairs,
- escalator,
- platforms,
- service desks,
- lifts,
- concourses,

plus several others. Each of these is defined in terms of their length, width and connectivity. These figures effect the flow rates and congestion calculations. At specific events, such as passport control, the model employs pre-defined flow rates, whereas at moments of congestion, caused by large numbers of passengers, or bottlenecks, it utilises speed/flow and time/density relationships in combination with the block information.

Using this information, the system simulates the movement of the passengers through the enclosure, displaying the results in either 2-D (see Figure 3-2) or 3-D (see Figure 3-3), allowing the user to view congestion, passenger build up and flow rates. It is capable of tracking passenger facility-use, closing and opening check-ins, and restricting access to certain structures, during the simulation. Using this information, Paxport/Pedroute produces the 'Level of Service' [66] of the specific section. According to the developers a simulation of this type with 30,000 passengers requires 16 hours on a 50Mhz 486PC with 8MB RAM[39].

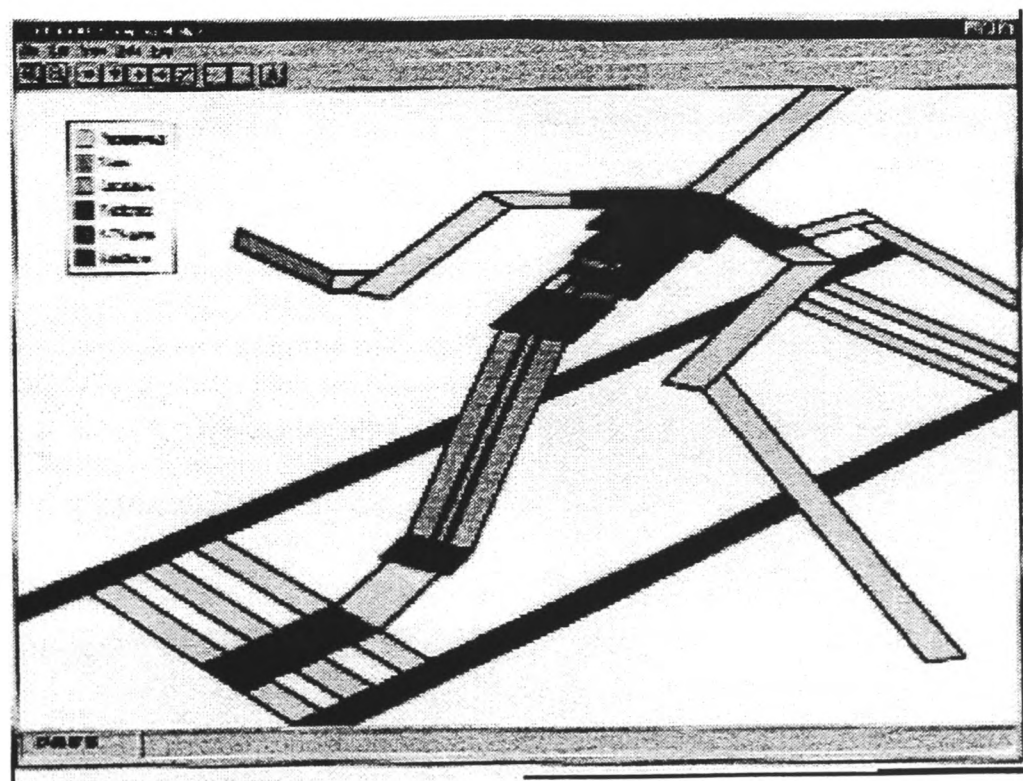


FIGURE 3-3:THE PAXPORT/PEDROUTE 3-D DISPLAY[172]

Once complete, the output contains the flow rates and delays of either the individual blocks or the complete enclosure, and the predicted level of service expected, measured in terms of space per person. These figures can then be used to determine the maximum

capacity of the terminal, the necessity of structural changes, and the feasibility of commercial (e.g. retail) prospects at specific locations within the enclosure (see Figure 3-4). An additional module is available that enables a more detailed analysis of the data, although little information is available concerning this option. Future developments intend to simulate evacuations and the development of safety procedures.

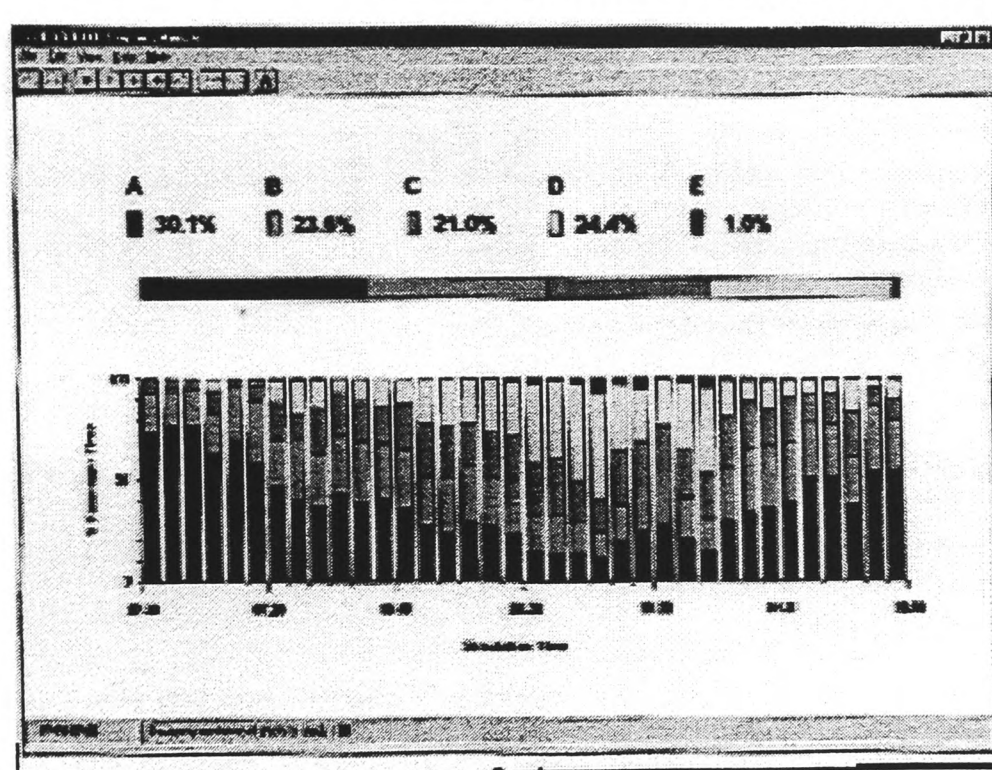


FIGURE 3-4: THE ANALYSIS OF SERVICE LEVELS PROVIDED BY THE PEDROUTE GRAPHICS MODULE [172]. Although this model does not explicitly include behaviour, it does attempt to represent the delays caused by certain behaviours by allowing passengers to stop near facilities, indicating that the delay is caused by some usage. The passengers have no affect on the outcome other than to increase congestion. The model does not contain a hazard model.

As it deals with thousands of occupants, individual occupant definition is considered impractical, and hence the group definition is implemented. However, the attributes inherited from these groups are concerned with administrative and temporal differences, instead of the change in flow caused by the arrival of such a group. It would be preferable to represent the flow rates of different types of passenger, and therefore the effects on the incumbent population of the arrival. While the time at which large numbers of new passengers enter the system is vital to the flow calculations, arguably it is no more important than the speed of the passengers within such flows.

It is also impossible to identify the location and trajectory of any passenger to any degree of accuracy, due to the use of the coarse network. Indeed, the production of the 'Level of Service' [66] does not require even the group location to be calculated, only the population density of specific compartments. It is not clear how passengers are made to

interact with signage, or how such signage is represented inside the geometry.

The authors could find no evidence of validation or detailed technical publications concerning this model.

B)INDIVIDUAL PERSPECTIVE { E[36,37] , EP[29] ,ES[32-33],EA[167] }

I)RULE BASED BEHAVIOURAL MODELS{ E[36,37] ,EP[29] ES[32-33],EA[167]}

**EXITT [36-37]**

**EXITT**, developed by Levin at NIST (The National Institute of Standards and Technology), is designed to model residential occupancies, and takes individual actions as a function of time, smoke/fire, location, detectors, the gender of the individual, individual capabilities and the status of individuals, and determines future actions by linear programming techniques in relation to these functions. However, the model does not consider heat or toxic effects of the environment on the occupants.

It is DOS based (written in BASICA) and applies a coarse network approach, with a limit of 12 coarse nodes, limiting its application to enclosures with up to 12 compartments. Information concerning the maximum number of occupants modelled or the average run time of EXITT is not available.

Within EXITT, human responses are deterministic, with the majority of behavioural assumptions derived from studies concerning the survivors of residential fires. However, several assumptions used in the model are based on those held by its developer. The movement of people is not only deterministic, but is determined wholly on the class of the individual, so that two individuals of the same class will move in the same pre-determined manner, based on the same decisions. Movement is set to a basic speed of 1.3 m/s. However this may increase/decrease in a discrete fashion depending on whether the occupant is upright or crawling, or if the occupant perceives a serious fire.

Through the techniques highlighted above, behaviour such as investigation, rescue, limited communication, offering assistance, exiting, and differing response times (which included being asleep or awake), are simulated. One of the more unique features used in this model, is the impact of noise on the individual. This impact is dependent upon the severity of the noise level in the occupant's vicinity. This has a small effect on behaviour at extreme levels. Within EXITT, individuals are categorised as capable or incapable of



moving by themselves, and this is taken into account when movement actions, and decisions are made.

If a fire is present, an individual's response time ( $T$ ) is determined according to the following function [36],

$$T = 70 - 4 * (C - 20). \quad (29)$$

$C$  is a function determined from the following equation,

$$C = (A - N) + X_1 + X_2 + X_3 + X_4 \quad (30)$$

where  $X_1$  is the sensory impact of being awake and seeing the flames,  $X_2$  represents the impact of the occupant smelling the smoke,  $X_3$  is the impact of the occupant seeing the smoke,  $X_4$  is set to 0 if the occupant is asleep and 15 if the occupant is awake. The ' $A$ ' variable represents the effect of the smoke detectors, while the ' $N$ ' represents the background noise. This equation is based upon the research conducted by Nober et al [173]. This research, and therefore the equations above, assume that the response is a function of impacts derived from different perceptions. This position is itself derived from Fechner's Law [174] that states that the intensity of perception varies directly with the log of the physical stimuli. These contributing factors are measured in different units, with the transformation rates provided by the user. These rates were not calibrated with real-life data and the developers saw this as an area for future work.

It should be noted that Nober's original work was only concerned with the effects of smoke on the occupants, and made no mention of the other variables used in the equation above. The developers also make the assumption that the variables in this equation are simply additive. The developers provide no experimental justification for this assumption and they comment,

*"The model.... assumes that the response is a function of the sum of the impacts of different sensory cues. This assumes that the relevant aspects of the perceptual processing of olfactory, visual and auditory cues are similar."* [36]

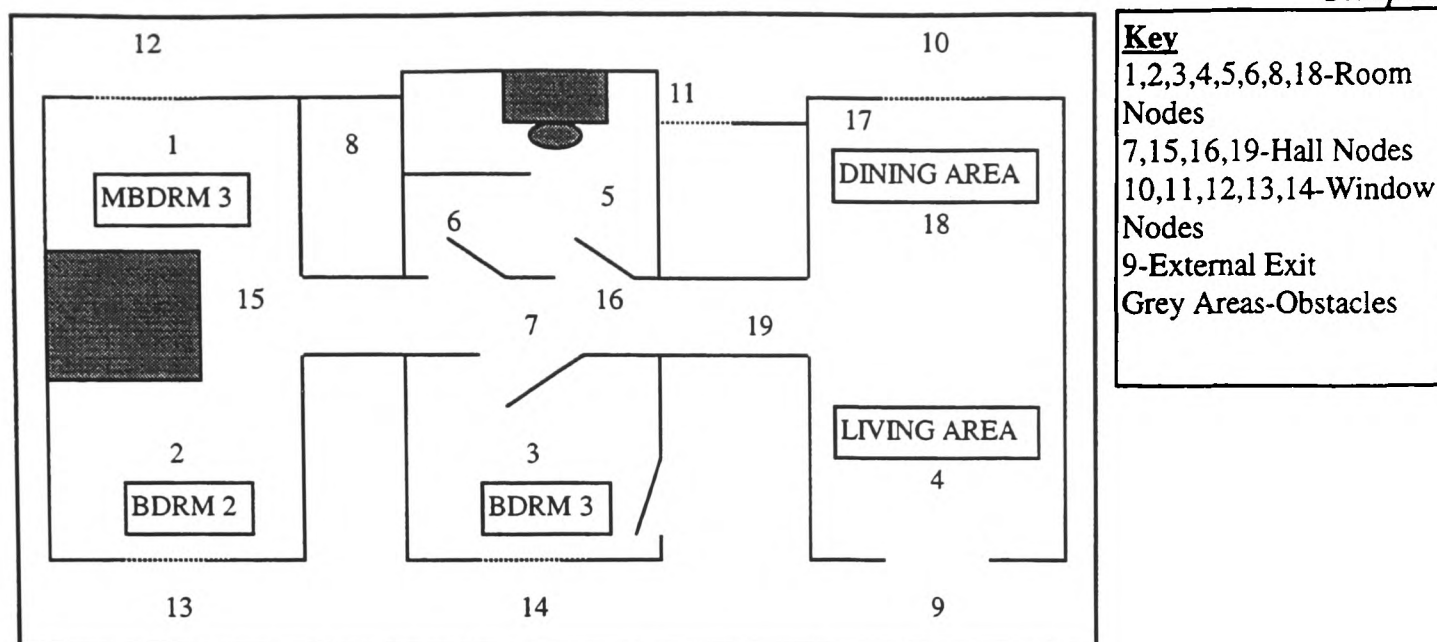
Within EXITT route planning takes into account the density of the surrounding smoke using equations identified by Jin [9]. Individuals might venture through smoke, depending on certain individual thresholds. Once the possibility of movement is determined, a shortest path algorithm is used that assigns demerits to paths and selects the optimal path as being that with the lowest number of demerits. This algorithm only functions at the level of the coarse network, so that movement inside the nodes is not

calculated. Delays in choice are created according to personal characteristics, whereas movement rates are extrapolated from Jin's work. The so-called 'panic' movement is derived from Jin's work on movement through smoke. No evidence is provided to support the validity of this extrapolation.

Within EXITT, events and interactions are carried out on a coarse node network, and occur in a discrete manner, with decisions taking place in reference to one of the coarse nodes (which might be a corridor, a room etc.). The behavioural considerations are only taken into account at these points. Therefore the influences of the decisions only extend to the movement between nodes, which may or may not be occupied by other occupants, and cannot take into account the individual trajectory or decision making process inside nodes.

Figure 3-5 represents the rescue of a child by its father in a domestic fire situation as would be predicted by EXITT. The events and decisions occur at predetermined locations. The actions of the father are completely undetermined in-between nodes. We can only assume that, for instance, he travelled between nodes 2 and 16, and was travelling at the same speed as that at which he was travelling at node 2, and maintained this speed throughout this journey. (However, this type of analysis is only available once EXITT is used as part of the HAZARD I model). In this sense, the movement rates are used to determine the time of arrival at the next node, instead of providing an accurate location of an individual, which is generally the case in coarse node networks.

As EXITT only considers enclosures made up from a limited number of nodes that tend to be of a small size, the application of a coarse network may not be considered severely detrimental to the overall performance of the model. However, it will detract from the accuracy of the behavioural model.



- Smoke detector sounds at 90 seconds.
- Father starts investigating at 100 seconds.
- Father arrives at node 16 ( a section of corridor) at 106.3 seconds. Sees moderate smoke at node 19(further stretch of corridor). Ends investigation.
- Father starts going to rescue baby at 109.3 seconds. (Since father has seen moderate smoke, his travel speed is increased).
- Father arrives at baby in room 2 at 113.6 seconds.
- Father starts to carry baby to front door at 117.6 seconds.(Father travels at slower speed when carrying baby.)
- Father and baby go through moderate smoke in living room and leave by node 9( front door) at 127.5 seconds.

FIGURE 3-5:EXAMPLE OF THE MAJOR SIMULATION EVENTS WITHIN EXITT. REDRAWN FROM ORIGINAL DIAGRAM[36]

Finally, EXITT lacks any form of social and group activity, as well as fundamental activities such as fire-fighting and re-entry.

### EvacSim [32-33]

**EvacSim** [32-33] is a discrete event simulator developed at the Centre for Environmental Safety and Risk Engineering (CESARE) in Australia, which incorporates the QNAP2 (Queuing Network Analysing Package) queuing tool. This indicates that

*“Each person is followed closely and that critical events in his movement process are identified. These events are then scheduled into an event calendar, corresponding to an event for another person, or a change in the accident scenario.” [32]*

It is a SUN workstation-based package, which claims to allow the population to interact with each other, and with their environment in both a deterministic and stochastic fashion, while still enabling the modelling of large populations. This provides knowledge of individual movement and therefore the ability to identify critical events, during the evacuation.

Occupant actions are determined through a set of matrices (see Figure 3-6). These are

applied within a coarse network model, compromising the accuracy of the occupant's location. Individual actions are dependent on the severity of the situation, as determined by the individual through their perception of cues. This perception determines a range of actions, whose choice will be influenced by role allocation. The environmental cues, as perceived by individual occupants, are represented through the use of the physical scale, which includes a smoke obscuration level, and the air temperature.

Activities specific to certain types of role are possible such as the ability to search a building for a warden. To cope with the level of complexity that these matrices entailed, the routes that individuals follow is based on an orthogonal distance approach, introduced by Takahashi. Movement and behaviour is determined according to a number of physical and psychological cues, but not social variables.

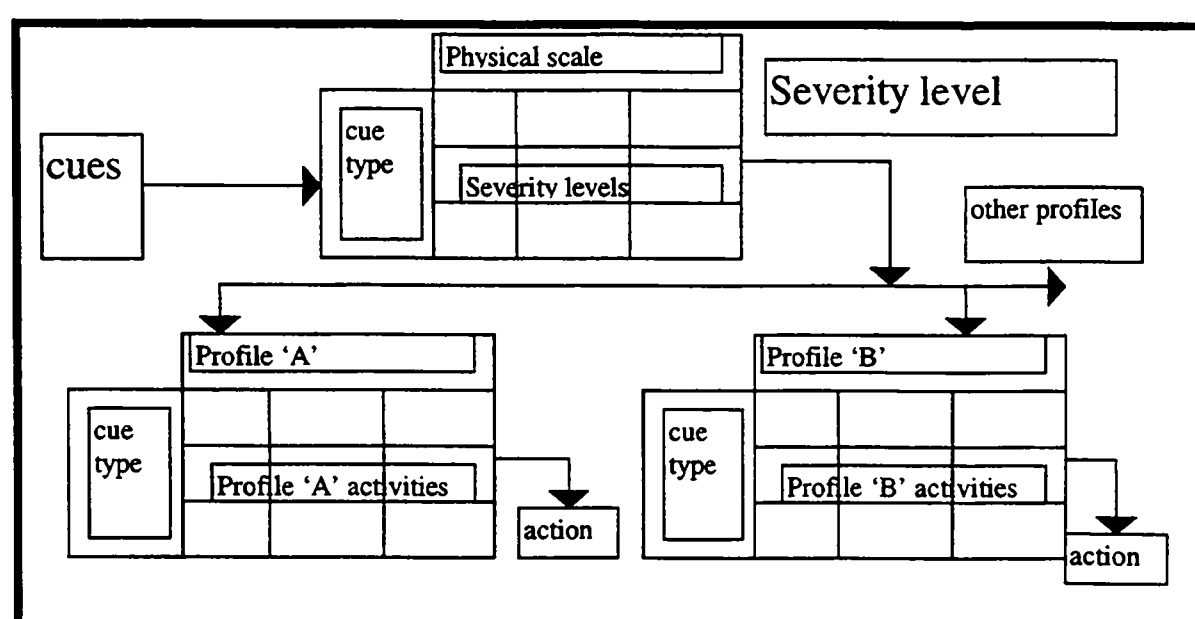


FIGURE 3-6: MODELLING INDIVIDUAL OCCUPANT ACTIONS IN RESPONSE TO INCOMING CUES USED BY EVACSIM. CUES ARE RECEIVED BY SEVERITY MATRIX, WHICH DETERMINES THE ACTIONS TAKEN BY AN INDIVIDUAL, DEPENDING ON THE INDIVIDUAL PROFILE.[32]

EvacSim has a comprehensive list of behavioural features, although the methods it uses to implement these features are somewhat unclear. Those that are identified include communication and group behaviour. Communication is divided into the transfer of the severity level, where those near to an individual with a heightened sense of severity will be effected, or through the enforced instruction of wardens. This behavioural effect is tempered by the implementation of the coarse network, as this communication information is equally distributed throughout the node. Group behaviour is simplified so that those choosing to join a group will automatically follow the leader's actions and communications.



The inputs that determine behaviour, are separated into the following categories:

- 1.Arbitrary severity scale determining the matrix of actions.
- 2.Physical cues perceived by individual.
- 3.Occupant response to perceived danger.
- 4.Physical attributes of individual.
- 5.Building Knowledge, including exit and floor-plan layout
- 6.Occupant profile defining individual role
- 7.Response profile table determining response to fire
- 8.Communication of fire knowledge.

All of these combined, determine the matrix and the particular cell inside that matrix, which might effect a specific action. As well as these general influences on behaviour, EvacSim employs a complicated exit choice procedure, which enables a number of considerations including the queue length, status, and position of the exit to effect the decision. The route choice is determined step-by-step. This means that an individual makes a decision at every node, although this would be equivalent to making a decision per room/segment of building. The travel speed is then calculated using a variable bilinear travel speed model, based on the following equation taken from Nelson and MacLennan[62]

$$F=SDW_e \quad (31)$$

where  $F$  represents the flow rate,  $S$  is the normal travel speed,  $D$  is the density at the chosen exit, and  $W_e$  is the effective width of the exit.

The travel speed is limited by internal occupant attributes,  $V_{maxH}$ , which represents maximum horizontal speed,  $V_{maxS}$ , which represents maximum stairway speed, and  $A_0$  which is the plan area occupied by an individual.

At each node there is a probability of moving onto a specific route,  $p_k(i,j,\underline{X})$ , where this can be interpreted as the probability of individual  $k$  moving from node  $i$  to node  $j$  when the system is at state  $\underline{X}$ . This probability is determined through the matrix and severity system identified, as well as the perceived shortest route rule, including a personalised form of the structural map [175]. Once queues are formed, they are resolved on a First In First Out (FIFO) basis.

The model developers identify the lack of evidence for many of the assumptions used in the programme, as well as certain forms of behaviour that were lacking, including sleeping, and the activities of the elderly, as being areas for future work.

It is one of the few models to incorporate an individual's psychological and physical reaction to the fire which then act as cues to specific actions. As well as this, the probability of an action is dependent upon an occupant's prior activities. It is not clear whether these activities are deterministic, stochastic, or act as a function of the event, nor is it clear how these are resolved inside a coarse network (e.g. does the distance from a fire effect the severity of the reaction to the fire, and if not, is the effect uniform throughout the node?).

EvacSim does not possess any form of toxicity model, and ignores any physical interaction between occupant and the fire event, other than the possibility of a change in direction, due to the existence of smoke and fire. It also suffers from the lack of a graphical user interface, and supplies output data in a coded text format (see Figure 3-7).

```
347.8s:[1 1 e42 0o 1 x34200 y15000 s1] going to exit opening 34
359.8s:Occupant 1 has exited the building
363.2s:[112 e34 o 3 x33000 y22000 s2] seeks enclosure 38
363.2s:[112 e34 o x33000 y22000 s2] going to exit opening 28
369.5s[112s e35 o 3 x33400 y17000 s2] going to exit opening 29
```

FIGURE 3-7: EXAMPLE OF EVACSIM OUTPUT. EXAMINE THE X AND Y CO-ORDINATES AND THE WAY IN WHICH THEY ARE ROUNDED TO THE NEAREST UNIT OF A HUNDRED. [32]

EvacSim incorporates one of the most complete behavioural models implemented by a functioning model. It explicitly caters for the movement of disabled occupants, and how this might effect their exit procedure. However, the fact that it is based on a coarse node network makes the wayfinding system somewhat redundant, as the probabilities refer to moving between rooms, instead of moving around rooms, with all of the local navigation required in such movement. This produces a less detailed account of occupant movement that would be especially noticeable where occupants have unique or unusual traits such as in the case of disabled occupants. Local difficulties that disabled occupants are faced with can therefore not be simulated, undermining the ability of EvacSim to accurately represent this form of occupant movement. Also, it is difficult to identify where and how the sophisticated social interactions, such as group behaviour, which are claimed to be modelled, actually occur. The occupants appear to be locked into a grid system (see Figure 3-8). However, this grid system itself is aligned to the coarse network, providing no greater precision. In such a case, the occupants are incapable of interacting at close quarters, therefore nullifying the completeness of the behavioural model itself.

If group behaviour referred to activities of entire nodes, then the main reason for

implementing group behaviour, i.e. the interaction between members of groups and those non-members, would be somewhat redundant. Unlike EXITT [36-37], EvacSim is claimed to be able to cope with larger populations and enclosures. It may be expected that the implementation of a coarse network for larger geometries would reduce the effectiveness of the behavioural model.

EvacSim was assessed for viability through a test carried out by the developers, using data from a real incident that occurred 12 levels above the ground, in a partially occupied building [33]. The developers saw a flaw in this type of validation as the results may be very specific, and might not be generalised, as

*“If there were other possible fire scenarios which has a similar or greater likelihood of occurrence but perhaps with more severe outcomes, then they need to be investigated.”[33]*

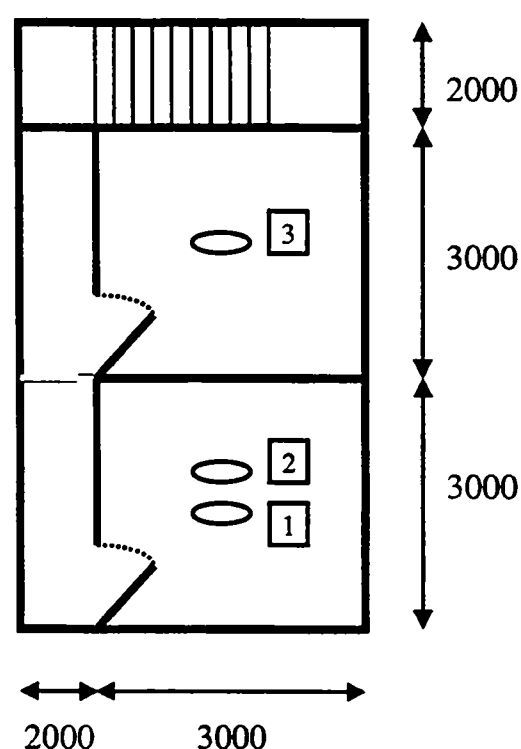


FIGURE 3-8: REDRAWN FROM THE ORIGINAL DIAGRAM. ILLUSTRATES THE 'SNAPPED' GRID SYSTEM IMPLEMENTED. NOTICE THE CENTRAL POSITION OF ALL OF THE OCCUPANTS.[32]

The structure was sparsely occupied at the time, with a maximum of 24 occupants on each level. This prevented any meaningful evaluation of the EvacSim movement model. The evaluation was therefore limited to the sequence of behavioural activity, instead of evacuation times, therefore concentrating on the strengths of EvacSim. However,

*“Accounts from occupants reporting their experiences in the fire varied even within the same tenancy and it was therefore difficult to determine the actual events which occurred. The incidents reported here may therefore differ to some extent as to what had actually occurred. In addition, because the only floor-plan that was available was without wall partitions, the floor layouts presented herein have been approximately determined.”[33]*

This highlights a flaw in the validation procedure, which indicates the necessity of further more vigorous validation. These results suggest that while EvacSim is capable of representing a wide variety of behavioural activities, discrepancies occur in the time occupants require completing these tasks.

#### **E-SCAPE[29]**

**E-Scape** is a PC-Windows-based real-time behavioural system, which attempts to map the cognitive decisions during an evacuation. The developers see two factors as fundamental in this attempt:

1. The time taken for occupants to initiate egress.
2. The egress route.

All other actions are seen in context with these two fundamental factors. To run the model, the user is required to define the dimensions of the structure, the type of structure, the position of occupants, and the exit choice factors.

It is based on a cognitive model which separates behavioural influences into Performance Shaping Factors (PSF), which are Structural (catering for the work environment), Effective (cultural and social factors), Informational (cues and communication) and Task and Resource Characteristics (tasks in progress). The PSF model is claimed to be automated using the E-Scape simulation. However, E-Scape simulates actions, not by the effect or the success of the action, but the time it takes to perform the action, due to the processing expense required for such detail. It is not obvious as to how the individual can then have any effect on the environment within such a system, or whether the success or failure of actions is accounted for.

The structure is mapped through the use of a coarse network (see Figure 3-9) and is then identified as a specific type, such as a hospital, a public building, an oil rig, etc. This label then influences the way in which the individuals, being allocated to specific nodes, will respond to the cues and stimuli provided by the model, in their choice of exit route, and their response time. In this way, the PSF are implicitly defined within the structure.

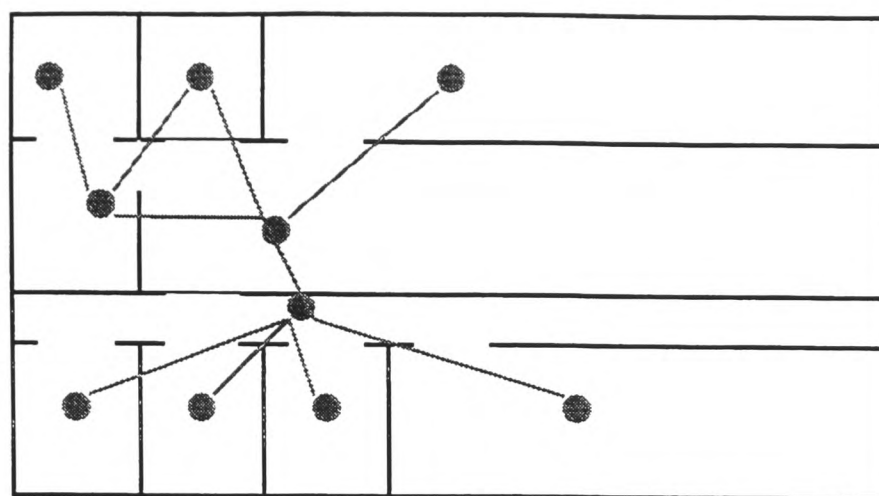


FIGURE 3-9: E-SCAPE REPRESENTATION OF A PLATFORM OF AN OIL-RIG. EACH ROOM IS REPRESENTED BY A SINGLE COARSE NODE, AND THE CONNECTIVITY IS DISPLAYED IN TERMS OF LINKS.[29]

The developers assume that the delay prior to evacuation is built up from a number of actions:

- The number of people in a room. By increasing the number of people in a room, the probability of adopting behaviour increases proportionally, according to the ‘group conformity’ principle, whereby people follow others in their actions.
- The movement of others. By being present during the exit of another occupant, an individual would be influenced to also exit. This influence would rise with the number of people left, with each individual having a decreasing effect.
- The building type. Using data from previous studies, probabilities were assigned to delay times, depending on the use of the structure.
- The presence of smoke. The presence of smoke decreased delay times.
- The level of training. The effect of drills and training were seen to counteract each other, if both were present.

The developers assume that all of these factors are additive, and combine to produce a delay time to the environmental cues. However, it is not clear why these factors should be simply additive.

The distance from an exit, the use of an exit, the signage used, and the training provided affects the choice of exit. All of these factors affected the weighting for each exit, thereby defining its attractiveness. Again, it is not clear how these factors interact to influence exit selection in either reality or in the model.

Very little detail is given concerning the movement of people in the model, and how this

movement is achieved. One indication is given when the developers discuss the population of a node,

*“With an increasing number of people in a room more individual decision probabilities will combine. It could then be assumed that the probability for a person to leave a room with 50 people in it would be 50 times more likely at times than if the room were to only have one person in it.” [29]*

As with most of the information provided for this model, the emphasis is on the probabilities of moving from one place to another, rather than with the method of movement, and the effect that individual occupant characteristics have on this movement. Furthermore, its assumptions appear overly simplistic and not founded on experimental evidence. Although the developers go into some detail concerning previous work on occupant behaviour, they do not explicitly identify any of this data with a contributory effect on their behavioural model. There is no information provided concerning the expected run-times of the model, or the type of hazard model used, if any.

The model developers are critical of other models for relying heavily on flow functions to provide the mechanism for movement, but provide no replacement, other than to suggest the importance of behaviour during evacuations.

The model seems to abandon many of the suggestions produced by the PSF model, by only accounting for the time it takes for actions to be accomplished, and not the process of acting, and the effect this might then have. It is not clear whether the individual is a passive actor within the model, or whether he responds to the events surrounding him. In fact the only reference concerning the individuality of the occupants inside the model, concerns the response to cues. The developers comment that

*“For instance, an individual is more likely to “Deal with the Danger” stimulus if the location of the stimulus is known; the individual is male...” [29]*

No information is given concerning the method of locating individuals within a node, or whether the behavioural effects are distributed throughout the node, or localised to an individual. No reference is made to local navigation, and movement seems to be restricted to moving between nodes.

It is also unclear whether or not the model provides for the physical effect of smoke/toxic gas inhalation, to accompany the psychological response of the delay time effect.

The only validation provided by the developers is in the form of the model's ability to represent an enclosure (such as an off-shore platform) and not the model's ability at representing evacuation behaviour. The developers claim that this model is general-purpose in that it might be applied to a number of different geometry types. It is unlikely, given the present information, that this model could cope with the specific behavioural activities associated with different enclosure types which might be as diverse as hospitals and off-shore platforms.

### EVACSIM [167]

The **Evacuation Simulation** model was conceived and designed in France and Norway and was specifically created to facilitate the analysis of queues, bottlenecks and the resultant human behaviour, especially in concert with the existence of hazards. However, initially no means of representing the effects of an accident was included.

It uses the QNAP2 network analysis tool [167] to replicate the behaviour of occupants in relation to congestion and route-finding. It was produced to represent a number of environments including ships, offices, hospitals, hotels and sports arenas.

The model is based around four simulation aspects:

- The Network Model
- The Simulation Process
- Animation
- The Presentation of Results

The *network model* it utilises involves a *coarse node* description of the geometry. The nodes therefore represent non-uniform architectural constructions rather than uniform geometrical constructs. The engineer is required to provide details concerning the dimensions, occupant capacity, location and the initial occupation level of each node. If not supplied, the nodal capacity is calculated according to the dimensions of the node. There is no DXF or other CAD capability available to the user.

There are three different types of node: a *room*, a *corridor* and a *stair*. The speed of the occupant population is altered according to the properties of the nodal location.

Therefore the terrain and the population density within a node determine the occupant's speed. The nodes have *reaction times* associated to them. This is seen as representing the existence of alarm systems within that particular area, as well as any other factors that may influence the occupants' decision to evacuate.

These nodes are connected by links that establish the movement levels between the nodal locations. These also have a number of attributes associated with them including distance, familiarity, width and signage. The *familiarity* of the link determines the likelihood of a particular path being adopted by the occupant and is therefore of fundamental importance to the simulation of the wayfinding process. The *signage* attribute enables the familiarity levels of the occupants to be affected during the simulation, through the increased probability of adopting a particular route due to having signage associated with it. The width of the link determines the flow between nodes and is based purely on occupancy levels.

Each occupant is treated as a separate process. The user can determine the average walking speed (and walking speed distribution) of the population as a whole, that is then allotted individually to each occupant.

Each of these processes follows the same sequence of instructions. Initially the occupant completes any movement to a particular node. Once completed the occupant must decide upon a new movement. This decision is based upon the occupant's familiarity, the distance and direction to their eventual target and any signage that is evident. The occupant also has the option to delay movement according to congestion levels.

The overall evacuation time is therefore made up of the occupant's initial reaction time that is dependent upon the reaction times associated with individual nodes, the time the occupant spends traversing the geometry and the queuing time.

The model produces output concerning the evacuation time, exit usage and individual nodes.



TABLE 3-3: COMPARISON BETWEEN SIMULATED AND ACTUAL RESULTS [167].

Number of Persons	Actual Value	Calculated Values	90% Result Interval
Attempting to Evacuate	120	98	-
Successful	74	57.5	44-71
Dead in Cabins	66	85.5	76-96
Dead in Corridors	46	43.1	34-52

Several benchmark validation cases have been conducted alongside a comparison with an actual incident. This was based around the Scandinavian Star incident, on the 7<sup>th</sup> April 1990, where 158 people were killed at sea. The results are shown in Table 3-3 and demonstrate similarities although no overall evacuation time comparisons are made.

3.12FINE NETWORKS {BF [166], BG[14] ,EG[18-20] , EXO[5-7,21-27], F[49-50] , MG[38] , O-O[168], S[43-44] ,V[46-47]}

The Fine Network models are categorised according to the manner in which the population is specified, either using the a) Individual perspective or b)the Global perspective. The models are further subdivided according to the manner in which they include behaviour.

A)INDIVIDUAL PERSPECTIVE {BG[14] ,EG[18-20], EXO[5-7,21-27],MG[38],S[43-44],V[46-47]}

I)FUNCTIONAL ANALOGY BASED MODELS {MG[38]}

MAGNETIC FIELDS[38]

Okazaki and Matsushita designed a function-based model that represented the exit choice and wayfinding capabilities of individuals through magnetic fields. These magnetic fields were generated by Coulomb’s Law,

$$F = \frac{(k.q_1.q_2.r)}{r^3} \tag{32}$$

where  $q_1$  and  $q_2$  are the intensity of the magnetic loads of pedestrian and goal respectively,  $k$  is a constant,  $r$  is a vector from a pedestrian to a magnetic pole, and  $r$  is the length of  $r$ .  $F$  is a vector representing magnetic force.

Pedestrians and obstacles are positively charged, and therefore repel each other, whereas the exits (goals) are negatively charged. It is not obvious as to how the obstacles are prevented from attempting to exit, without some explicit direction.

The individuals are calculated separately, but respond to the fields in a uniform manner,

so that although individual trajectories can be analysed, all individuals respond identically to the same field.

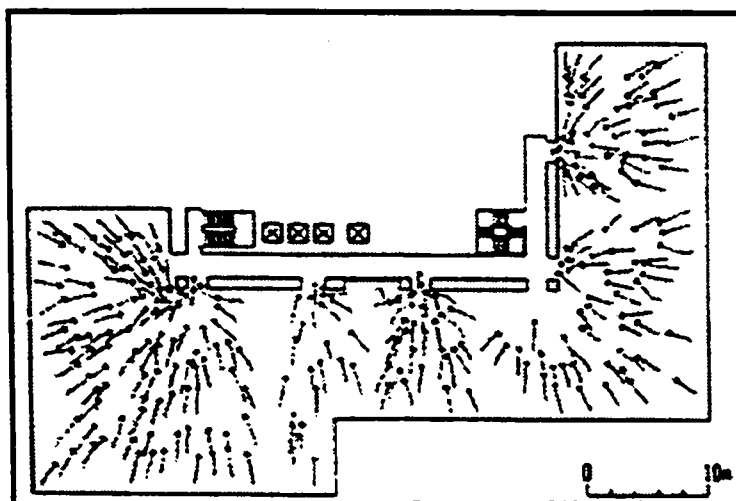


FIGURE 3-10: MAGNETIC FIELDS ACTING UPON INDIVIDUAL OCCUPANTS IN MODEL.[38]

This system works on a 0.1-second clock, on which basis individual data is updated. The data that is held on each individual includes location, velocity, time to start, orientation, and destination. The location is determined using a co-ordinate system, thus enabling trajectories to be followed closely (see Figure 3-10).

If the number of individuals is increased above a certain threshold, groups of individuals are treated as one, responding to the magnetic force uniformly, therefore lessening the computational expense. The developers explained,

*“If a lot of pedestrians should appear in the plan, pedestrians are divided into groups and data are given to each group. Each group has a common destination, orientation, start time, and method to walk.”[38]*

It is unclear whether the developers intended this as an attempt at modelling affiliative behaviour, or whether it was simply a device to save computational time. Although it has no behavioural model, it does use a complex queuing system which distinguishes between counter/gate/door(entrance and exit) queues. The model therefore attempts to simulate behaviour around the objects, catering for the expectation of individuals as they approach different styles of exit.

The only other behaviour considered, the movement towards the nearest exit, was completely determined by the equation defined above. There are three distinct forms of exit choice:

1. Route previously indicated.
2. The shortest route.
3. Wayfinding, whereby the individual seeks a goal.

Once the exit has been allocated, the person movement is determined by the magnet

equation defined earlier. A complicated deflection equation is used to simulate the local movement of individuals as they interact with other occupants,

$$a = VA \cdot \cos a \cdot \tan b, \quad (33)$$

where  $a$  represents acceleration,  $VA$ , the velocity of the individual under question, ' $a$ ' is the angle between the relative velocity of the individual under question, and the other occupant, and ' $b$ ' is the angle between the same relative velocity, and a circle defined as a Pedestrian Area Module, which extends 60cm from each individual. The implemented movement model is not location specific, so that different compartments are treated uniformly, not taking into account the differences between stairwells and corridors, for instance.

The model does not attempt to simulate the effects of heat, smoke, toxic or irritant gases. No computer platform specification, run-time, validation or parameter limitation information is provided.

#### **A)II)IMPLICIT BEHAVIOURAL MODELS{S[42-44] }**

##### **SIMULEX [42-44]**

**SIMULEX [42-44]** is a C++ based package which through the use of spatial analysis, concentrates on the physical aspects of the population and the way these effect evacuation times. By focusing on ideas such as personal space and collision angles, it may be claimed that psychological aspects of evacuation behaviour are inherent in the model, as the individuals are effected by their immediate surroundings; primarily other occupants. The model was originally developed at Edinburgh University and is now maintained by IES Scotland.

Simulex caters for a number of objectives, which dictate the basic structure of the model, and go some way to describing the model:

1. Define the building space
2. Define escape routes, in context with building space.
3. Define individuals, using personal characteristics and location
4. Definition of escape route must cope with overtaking and 'localised route deviation'
5. Incorporate speed reduction effects due to surrounding population, in form of

'jostling' and overtaking .

The floor-plan is created, allowing the user to input the enclosure data directly, using a pre-existing floor-plan.

The exit routes are determined using a distance map which subdivides space into a collection of nodes measuring 0.25m x 0.25m (although in recent versions this has been altered to 0.2m x 0.2m) [44]. These nodes are uniform, therefore being unable to represent local alterations in the terrain [44]. A distance map is determined by defining a small mesh in the region of 8 cells by 8 cells, or extended to include much larger meshes, usually 21 cells by 21. The distance map is created by determining the Euclidean distance between a central node and those in a surrounding area. A similar procedure is then carried out for all other nodes forming an overlapping set of grids. The smallest values are then retained to build up an optimal route.

These are then organised into contours (or 'spatial mesh' value bands), where each contour has a calculated distance within a certain range depending on their distance to exits (see Figure 3-11). The population attempt to move around this system in an optimal manner, which results in a motion perpendicular to the contours, although this movement is dependent upon the ability of occupants to overtake successfully. The contour values can be altered by adjusting exit coefficients to account for the desirability of each exit.

The occupant population is assumed to be between the ages of 12 and 55, with a random gender distribution, and travel speeds between 0.8-1.7 metres per second. The initial orientation of an individual is also randomly generated. These assumptions limit the scope of the model, excluding even the implicit modelling of the young and elderly, or the disabled, in the version described in the literature [42-44]. These attributes can not be individually defined for each occupant. Once defined these individual attributes remain constant throughout the simulation, and are not effected by the extreme conditions of the evacuation.

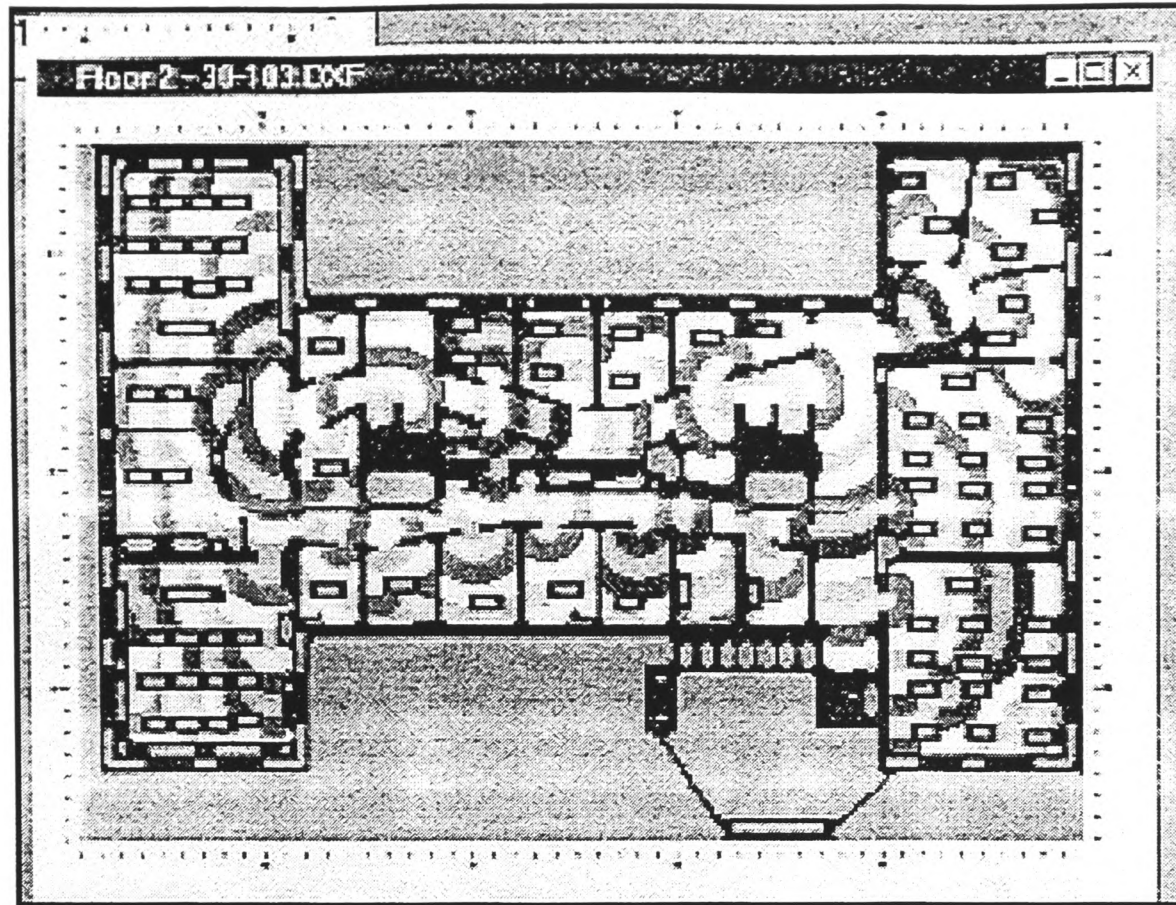


FIGURE 3-11: SCREEN DUMP FROM SIMULEX (VERSION 3.0), WITH THE SPATIAL MESH/ 'CONTOURS' CLEARLY VISIBLE THROUGHOUT THE ENCLOSURE [44] .

At each time-step (0.1 of a second), the positional parameters for each individual, i.e. angle of orientation and distance to the exit are recalculated. This calculation is repeated in the following loop;

*Execute decision and movement process for all occupants*  
*Reassess order of data storage*  
*Remove all occupants with a distance-to-exit of zero*  
*Update the time and number of occupants*  
*Repeat all of above.[42]*

There is no social interaction as such, and although the physical nature of the surrounding structure may have influenced direction, the status and the use of the building exert no influence on the population.

There is no mention of behavioural considerations in the movement decision sequence. Individuals move in as close to optimal manner as possible, until encountering obstacles. These may cause complex overtaking algorithms to be activated, in a manner that might be compared to that used by Okazaki et al [38]. These algorithms examine different approaches to the change in direction until an optimal direction is found. The algorithm allows the occupant to navigate around the obstacle as efficiently as possible, and as such does not recognise the individual as being different to any other object. Due to this lack of recognition, there is no sociological interpretation of such an event involving either communication or other social interaction. Only physical considerations such as

'jostling' and 'angle of orientation' are accounted for. Furthermore, Simulex does not define occupant responses to the fire-hazard, therefore preventing people-environment interactions taking place.

Simulex calculates the movement velocity of an individual using the following equations,

$$d = \sqrt{\frac{1}{D}} \text{ (metres)}, \quad (34)$$

where 'd' represented interpersonal distance (see Figure 3-12), and 'D' the population density, which leads to a reduced speed calculation of,

$$\text{Reduced\_speed} = \frac{V(d - 0.25)}{0.87} \text{ (metres/second)}, \quad (35)$$

where 'V' is allocated unimpeded walking speed. These calculations are applied when any two individuals are within a specified distance or comfort zone of each other.

These calculations completely determine the movement of the occupants in relation to other people with the crowd flow being influenced according to the data provided by Ando et al[152]

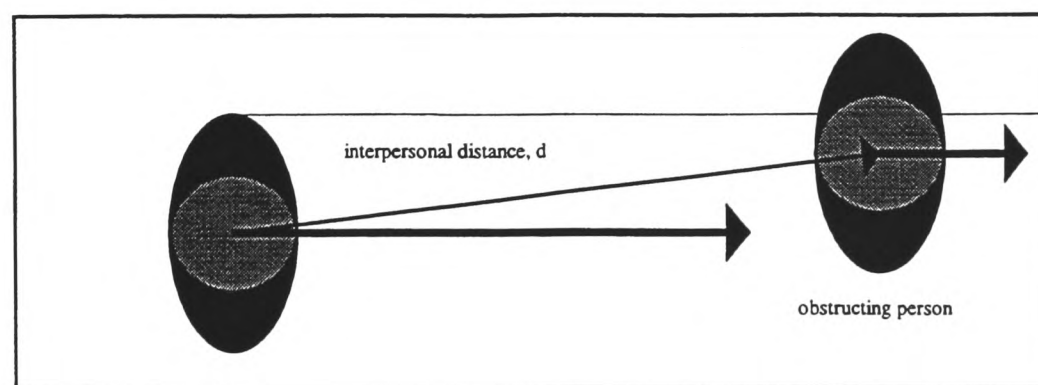


FIGURE 3-12: REPRESENTATION OF HUMAN INTERACTION IN SIMULEX. THE INTERPERSONAL DISTANCE IS USED TO DECIDE WHEN A INDIVIDUAL WILL ATTEMPT TO GO AROUND ANOTHER INDIVIDUAL.[43]

The model described in the literature available lacks most behavioural characteristics such as 'aggressiveness', 'familiarity with the structure', 'awareness', 'eagerness', response to alarms etc.

The only apparent psychological/sociological concession is the existence of the comfort zones that may cause a slight deviation of travel angle. This should be considered more of an instinctive response, than a behavioural response. Individuals are capable of 'twisting' away from obstacles up to an angle of 100°, based upon research by Rickets [176].



Simulex invests a considerable amount of computer resources in computing the angle and position of individuals to great accuracy. It is not clear how these then combine with the fundamental space discretisation represented by a node area (0.25m x 0.25m), whose definition seems not as refined. The developers claim,

*“The 0.25m resolution of the distance map does not dictate the accuracy of the route calculations, because the only two functions that the distance map performs are:(a) to yield a value for total distance to exit, and (b) to enable the immediate optimal angle of travel to be assessed from any point in the building.” [42]*

Therefore, the calculations concerning the change of angle would not be effected by the mesh system. However, the final resting-place of the occupant would have to be aligned with the mesh system, no matter how accurately the angle is calculated. It is also not clear whether the level of accuracy claimed -  $\pm 0.0001\text{m}$ , the equivalent of chest movement during respiration - is relevant or necessary. This is particularly true bearing in mind the spatial resolution of the model, the lack of behavioural characteristics, and the amount of computing required. SIMULEX requires up to 56 hours to compute an evacuation simulation involving a population of up to 3000 people using a 486DX2-66 PC[42].

In a recent development, SIMULEX v3.0 [44] has been introduced to cope with multi-storey structures. It also incorporates a response time into the simulation, and allows both group and individual occupant definition. To augment the psychological effects, a number of distance maps are stored in the computer's memory, allowing the user to determine which the occupants should implement. This is intended to simulate the different patterns egress routes might take, and may lead occupants to avoid the nearest exit. These distance maps are calculated according to different enclosure configurations, so that the exits may be more or less familiar in different distance maps.

Staircases (see Figure 3-13) are crudely treated as linear passageways irrespective of their actual geometry. This crude approximation is somewhat surprising in light of the great accuracy claimed in locating the position of individuals. Furthermore, travel speeds on stairs appear to be arbitrarily assigned and behavioural considerations such as staggering [177] appear to be ignored. At the time of writing, it is not clear whether this prototype is generally available.

Only a limited amount of validation is available for the Simulex model. The majority of the validation available concerns the examination of the flow rates generated by

Simulex through exits, and the evacuation of a supermarket [178]. The flow rates were generated for a distribution of exit widths (0.7-3.0m), with a population of 100 people, and a population density of 4 persons/m<sup>2</sup>. The population was assumed to be calm. The model was found to produce flow rates which were in good agreement with previously published data[178]. During the comparison of exit widths, exits 'jammed' within 10-15 seconds when exit widths below 1.1m were used.

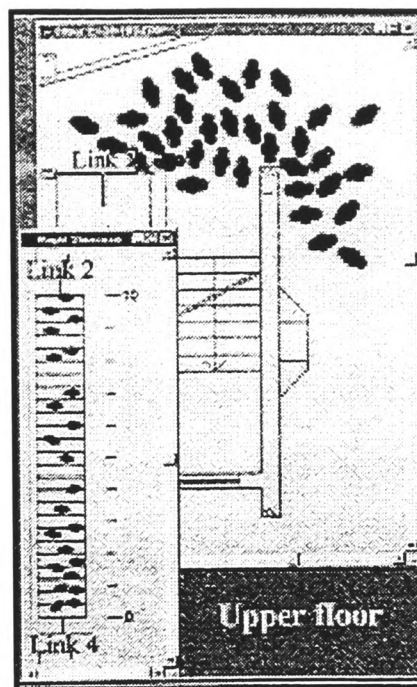


FIGURE 3-13: STAIRWAY GEOMETRY FROM VERSION 3.0.[44]

The supermarket demonstration was created using the floor plan of a store. Actual evacuation data was not available for comparison purposes. Two population sizes were used (1097 and 1919) to illustrate the patterns that evolved during the evacuation. Occupants were assumed to move towards the nearest exit. Using standard 'engineering' calculation procedures, with a walking speed of 1.19 m/s, the developers generated the expected 'optimal' evacuation times of the two populations as being 35 and 51.3 seconds respectively. SIMULEX predicted the evacuations as being significantly greater than these, being 81% longer for the population of 1919. The higher evacuation times produced are to be expected from a simulation model.

More recently, Weckman [179] used the Simulex model to simulate the movement of 612 occupants from a theatre. The actual evacuation time produced was 330 seconds (only one evacuation was conducted). The average simulated time produced by Simulex was 320 seconds. The run times for each of the simulation times was recorded as being 2 hours [179].



### A)III)RULE-BASED BEHAVIOURAL MODELS{BG[14],EXO[5-7,21-27], F[49-50] } BGRAF[14]

**BGRAF[14]** is a stochastic model developed at the University of Michigan that aims to simulate cognitive processes during evacuations, through the implementation of a graphical user interface. It uses a modular system, which includes a decision and action generator module, responsible for the physical and psychological responses of people. Occupants possess a number of physical attributes including speed, location, and tolerance to smoke (the last of which is influenced by age, health, and previous training), and several decision attributes which are split into psychological properties (goal based responses) and cognitive factors (e.g. familiarity).

Occupants are assigned a goal, which they intend to move toward. Movement is determined using room-adjacency data to implement a travel algorithm. In this way, the minimum distance between goals is calculated, which then highlights the optimal path. These goals are identified using a weighting system based on familiarity, although there is no calibration supplied to support this system. The door status (whether they are open or closed), the position of people and the fire-spread rate are all determined by the user, interactively.

Occupant groups are used to classify the types of individual present in the structure. Once identified as a member of a group, an individual inherits that particular group's traits, thus making occupant generation a quick process.

In BGRAF an individual is seen as,

*“An information processing entity which displays goal oriented behaviour”[14]*

This should be compared with view taken by SIMULEX[42-44] that originally assumed optimality of response, in the context of route choice, and not in terms of goal attainment. Occurrences are seen as episodic, and are allotted a goal, which cause responses in individuals. These responses are taken from ‘action libraries’, which form the rule-base, and are built up depending on the goals identified, and influential factors, including the fire (people-environment interaction), the geometry (people-structure interaction), and other people (people-people interaction). See Figure 3-14.

These actions include:

- stay,
- exit,

- investigate,
- go to alarm,
- evacuate,
- fight fire,
- turn back,
- open a door.

Once an action is completed, all goals and influential factors are rechecked to determine whether the environment has been altered by the action, which would in turn affect the future behaviour of the occupants. Information is accumulated on the environment that identifies the particular action to be taken. The complexity of the environment has a direct effect on the performance of actions, as an action is more likely to be interrupted in a complex environment. Goals are determined stochastically, with the probabilities involved taken from actual evacuation evidence examined in the work of Bryan[60] although the developers saw the need for further calibration.

The structure, and the familiarity with the structure, is dealt with by incorporating an ‘information build up factor’, which is initially set as low, and could be altered depending on signage and familiarity. This figure then provides a weighting, which influences the wayfinding process.

The enclosure geometry is read in using a CAD system in which the fire threat is specified using a simplistic fire model. The model relies upon data provided by the user including the start time, the origin, and the spread rate. It is also capable of receiving data from the CFAST [180] model.

The model developers do not provide details concerning the methods used in this model, particularly the actual effects of the environment on the individual attributes, and the local navigation procedures employed by the population. It is not clear, for instance, how smoke effects the decision process, or what impact toxic fire products have on an individual. No direct information is provided concerning the run-time for a simulation, however, the developers did highlight some compromises that were made to the level of sophistication of the movement algorithm to cope with excessive run-times.

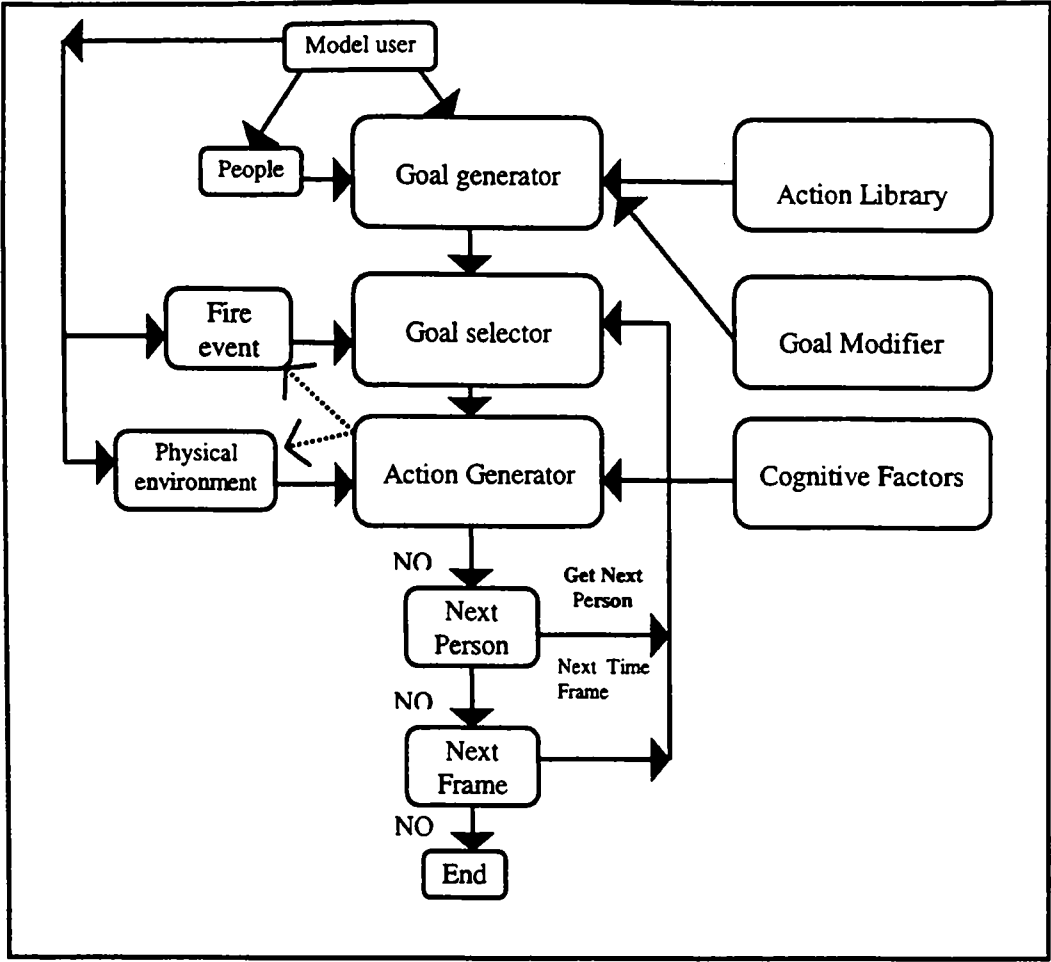


FIGURE 3-14: SCHEMATIC OF BGRAF SYSTEM. SOLID LINES INDICATE DEFINITE EFFECTS, WHEREAS THE DOTTED LINE INDICATES POSSIBLE EFFECTS.[14]

An attempt at validation was made by the developers, through comparison with a fire at a Nursing Home [181]. Of the 91 occupants situated on the fire floor at the time of the fire, information on only 22 was available. Unfortunately the available information did not include exit times. The comparison therefore focused upon the decision system; primarily the order and availability of specific occupant actions implemented during the evacuation. The decision system implemented by BGRAF during this validation was taken from the work of Bryan[60], and identified the correct proportions of occupant activities during ten simulation runs 80% of the time, at a 5% level of significance. However, this seems only to validate the implementation of Bryan’s work, and the Bryan cognitive model itself [60]. Although, this in itself is important, it cannot be judged in isolation from the movement model implemented. The examination of the movement model is not possible due to the lack of occupant exit times. This coupled with the large number of occupants missing from the validation, casts serious doubts upon the ‘validation’ quality of this work[181].

**BUILDINGEXODUS (VERSION 2.0) [5-7, 21-27]**

It should initially be noted that the examination of buildingEXODUS is carried out in greater detail, due to the availability of documentation and of the software to the authors.

EXODUS is a suite of software tools designed to simulate the evacuation of large numbers of people from a variety of enclosures. It was developed by the Fire Safety Engineering Group of the University of Greenwich. The suite currently consists of airEXODUS and buildingEXODUS. airEXODUS has been designed for aviation applications while buildingEXODUS is designed for applications in the built environment. The model is expert-system based, with the motion and behaviour of each individual being determined by a set of heuristics. It was developed within the environment provided by the Gensym software, G2 [182], and it has now been re-engineered in C++ using object-orientated techniques. This has enabled the use of data encapsulation and abstraction to ensure a crisply defined modular structure. Portability between platforms (such as PC- and workstation-based systems) is maintained by using the C++ library suite, XVT [183]. The system is configured to fully utilise 32-bit technology.

It provides a sophisticated graphical interface allowing the user to follow the evacuation through the visual representation of the event, or through the interactive examination of the data, which are displayed in tables and graphs (see Figure 3-16). This information can be examined post-simulation, as data is sent to a user definable external file, or whilst the simulation is taking place.



FIGURE 3-15: VIRTUAL-REALITY INTERFACE

More recently, a virtual reality post-processor visualisation interface has been developed to enhance the graphical features of the model (see Figure 3-15). The user now has the ability to interrogate a 3-D image of the simulation from a variety of angles, creating a greater understanding of the simulated events.

The graphical output can be de-activated, so that only the text-based results of the simulation are examined, through switching from normal mode to batch mode. This decreases the run-time of the simulation.

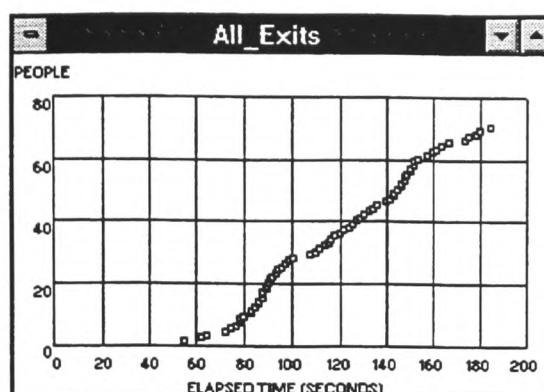


FIGURE 3-16: EXAMPLE REPRESENTATION OF GRAPHICAL DATA FROM WITHIN EXODUS. The model tracks the trajectory of all individuals as they make their way through the enclosure, or are overcome by fire hazards such as heat and toxic gases. The trajectory of any member of the population can be closely examined through the use of a utility that displays their path through the structure.

The spatial and temporal dimensions within EXODUS are spanned by a two-dimensional spatial grid (see Figure 3-17 and Figure 3-18), and a simulation clock. The simulation clock fundamentally controls the model. Decisions and actions can only occur with each 'tick' (equivalent to 1/12 of a second) of the simulation clock. The spatial grid maps out the geometry of the enclosure, locating exits, internal doors, seats, aisles, etc. Geometries with multi-levels can be made up of multiple grids connected by stairways. The structure, created inside the Geometry Sub-model, is built up through a two-dimensional network of fine nodes, at 0.5m intervals. The nodal connectivity is determined by the presence of arcs. This may be achieved automatically by the model, at either 45° intervals, or may be user-defined. Frequently used nodes, such as stairs and doors, may have specially defined attributes, and may be stored in libraries for re-use. The type of node also determines the difficulty an occupant has traversing it, with associated time delays, and maximum travel speeds, as well as adjusting behaviour to that which would be appropriate for that particular node, such as behaviour exhibited on staircases. The geometry of the enclosure can be defined using CAD, a geometry library, or interactively using the tools provided (see Figure 3-17 and Figure 3-18).



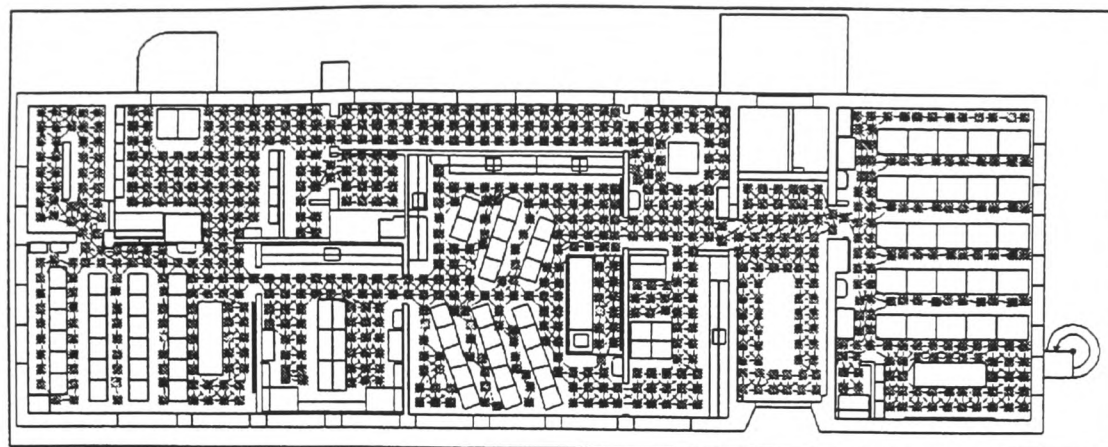


FIGURE 3-17: REPRESENTATION OF THE NODAL STRUCTURE IN BUILDINGEXODUS  
Each node has associated with it a number of attributes relating to the environmental conditions at that location, including the level of HCN, CO, CO<sub>2</sub> levels, oxygen depletion, smoke concentration, and temperature. This information relates to both near floor and head height.

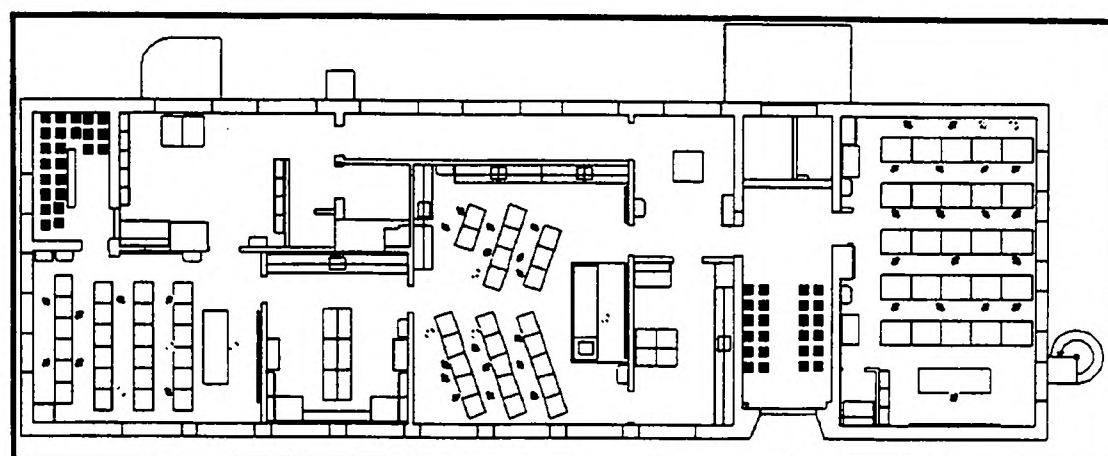


FIGURE 3-18: REPRESENTATION OF AN ENCLOSURE INSIDE BUILDINGEXODUS (SEE FIGURE 3.16), INCLUDING THE PRESENCE OF OCCUPANTS. IN THIS INSTANCE, THE NODES ARE NOT DISPLAYED, ALLOWING FOR A CLEARER REPRESENTATION OF THE OCCUPANT MOVEMENT INSIDE THE ENCLOSURE.

The EXODUS suite of software attempts to cater for the individual interacting with the fire, the structure, and the other members of the population. It does this through a rule-based system implemented through five interacting sub-models, identified in Figure 3-19. These sub-models interact, passing information between them, as identified in Figure 3-19. Each of these modules is responsible for a particular area of the simulation. The sub-model components employed by EXODUS, will now be examined in greater detail. In this discussion, the buildingEXODUS model is examined.

The Occupant sub-model defines each individual as a collection of over 20 attributes, which determine their response to the environment, and which in turn might be affected by the environment. These attributes can be categorised into:

- Physical Attributes- including the age, weight, gender, agility, etc.
- Psychological Attributes- including the patience, drive, etc.
- Positional Attributes-including the distance travelled, location etc.
- Hazard Effects Attributes-including exposure measures to heat and toxic gases.

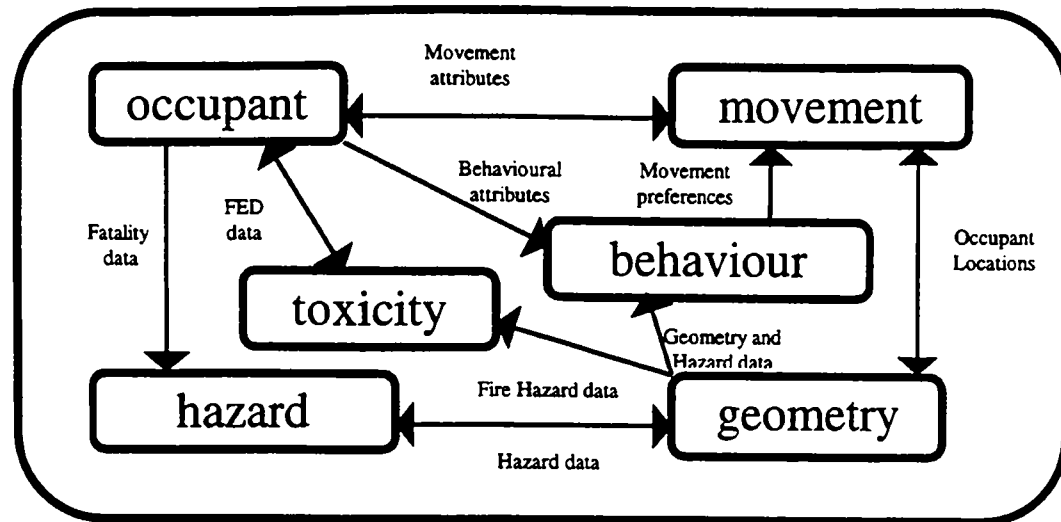


FIGURE 3-19: INTERACTION ON EXODUS MODULES.

These attributes define the occupants as individuals while allowing their progress through the enclosure and their status to be tracked at all times.

Through the manipulation of the mobility and agility attributes, the movement capabilities of disabled/handicapped individuals can be modelled. The mobility attribute has a multiplicative effect upon the speed and agility of an individual. By lowering this, an individual can be made slower and more cumbersome. The agility attribute itself can be manipulated, so that the occupant climbing capability or the ability to move across difficult terrain can be adjusted. This only models the difficulties with movement, and makes no attempt at the decision-based or procedural differences that might be present.

The Movement Sub-model is concerned with the physical movement of the occupants through the different terrain types. It determines the appropriate travel speed for the terrain type, and checks whether an occupant has the capability to perform a particular manoeuvre. This movement is governed by the mobility of each occupant, the environmental conditions, the terrain type, and the capability of the occupant to move in the desired direction. Within EXODUS the user has the ability to set, for each occupant, six levels of maximum travel speed. These are identified as FAST WALK (with a default speed of 1.5 metres/second), WALK (90% of FAST WALK), LEAP (80% of FAST WALK), CRAWL (20% of FAST WALK), STAIRS-UP, and STAIRS-DOWN. These represent the maximum unhindered speed the occupant can attain under various conditions. This information can be randomly generated within EXODUS, individually defined, or may be input using the population panel system that enables group definition. The default stairs-up and stairs-down speed is based on data generated by Fruin [66] and

is age and gender dependent.

The Hazard Sub-model controls the environment and allows the user to specify the scenario. The atmospheric environment comprises

- CO<sub>2</sub>
- CO
- HCN
- O<sub>2</sub> depletion
- temperature
- smoke

It does not predict the generation or spread of fire hazards but has the capability to represent the hazards generated by other models, including field and zone models.

The Toxicity Sub-model functions only when a fire hazard is present, and determines the effect of fire hazards on an occupant. It currently models the effects of the narcotic fire gases, heat, and smoke obscuration. The impact of the narcotic fire gases and heat is determined using a Fractional Effective Dose (FED) model. FED models assume that the effects of certain fire hazards are related to the dose received rather than the exposure concentration. The core toxicity model implemented within EXODUS is the FED model of Purser [108,109,113] although certain variations suggested by Speitel [61,62] are also available for use.

The FED model of Purser considers the toxic and physical hazards associated with elevated temperature, HCN, CO, CO<sub>2</sub> and low O<sub>2</sub> and estimates the time to incapacitation.

Within the FED model, CO<sub>2</sub> acts as a toxicant and as a hyperventilation agent, increasing the rate of uptake of other toxic gases.

Smoke is considered to reduce an occupant's capability by decreasing travel speed. The level of occupant immobility is based on the work by Jin [9]. Occupants are forced to crawl at critical smoke densities. These effects are communicated to the BEHAVIOURAL sub-model which, in turn, feeds through to the movement of the individual.

The behavioural system employed in EXODUS categorises behaviour into global and local strategies.



**Global Behaviour**

The global strategy is the default strategy of any individual situated within the structure. This default is determined via the use of a potential map, which is grown from available exits, such that, in an unbiased system, people will tend to evacuate towards the nearest available exit. This might change, if one exit becomes biased, which occurs if the individual is particularly familiar with that exit, or if for some reason that exit becomes more attractive (the closure of other exits, for instance). Therefore the number of people using specific exits will be skewed in favour of particular routes, due to their popularity (one being a main entrance, for instance). This might lead to an individual ignoring a nearby exit to head towards a more familiar distant exit (see Figure 3-20).

Evacuees, having decided which exit to head towards, then do so by lowering their potential in respect to that exit. This is achieved by moving onto a node with a potential lower than the one they are presently occupying. This system is dependent upon the way that these potentials are grown from each exit, effectively becoming a measure of distance from an exit, in nodal units, (which, in this instance are 0.5 metres).

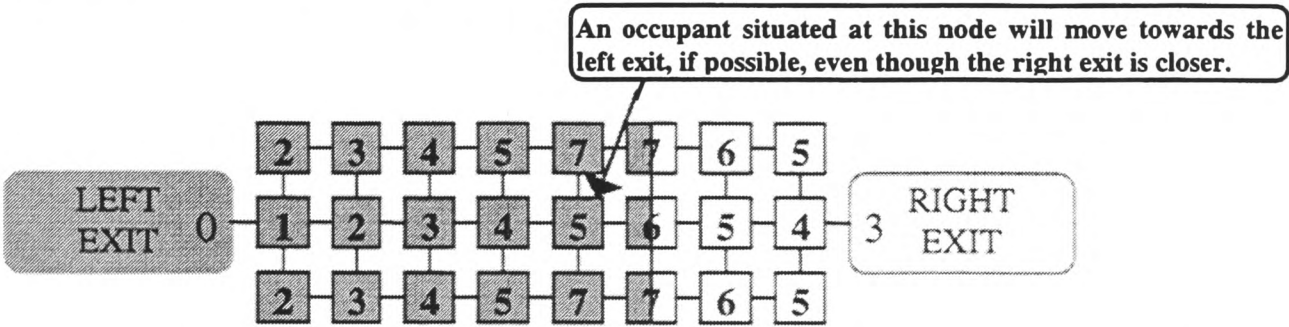


FIGURE 3-20: EXAMPLE POTENTIAL MAP, WITH THE LEFT EXIT MADE MORE DESIRABLE. THIS FIGURE LACKS ARCS AT 45° FOR CLARITY.

The global behaviour is an attempt to implement a basic evacuation strategy, catering for familiarity, through the potential map.

In building EXODUS, an exit is made more desirable by lowering the potential of the exit. This has a global effect, making the exit more attractive for the entire population. The user also has the ability of specifying a target exit for individual occupants or groups of occupants. This allows individuals to display a personal exit bias. This allows a more localised representation of the occupant's understanding of the enclosure, although is more time-consuming.

It is also possible to model internal exits through the use of Attractor/Discharge nodes. These allow control of the potential map within compartments. This produces a localised potential map, overriding the global potential map and also provides a facility to control the flow rate through the internal exit.

While the potential map provides an overall escape strategy for the occupants, this behaviour is usually modified by the occupants' local behaviour.

### ***Local Behaviour***

Global behaviour is followed until an event intervenes, such as an obstacle or individual obstructing their path to the preferred exit, on which occasion local behaviour is taken into account.

EXODUS has the capability of implementing two behavioural regimes: NORMAL and EXTREME behaviour. Under normal, non-emergency conditions occupants move under the influence of the potential map, i.e. occupants will generally move in a manner which lowers their potential. If this is not possible, a move onto a node with equal potential may be considered. If none of these options are available, the occupant will wait. However, under EXTREME circumstances, people may act in a more drastic and counter-intuitive fashion, thereby adopting a more indirect route to hasten their exit. If the EXTREME option is activated, an occupant may be prepared to increase their potential in the short term, once they have passed a patience threshold. It was felt appropriate by the developers that the user should enable this form of EXTREME behaviour when modelling an evacuation. The developers suggest that in simulations of 'real' emergencies the EXTREME option be used, while in simulating non-emergency or 'drill' situations the EXTREME option can be de-activated.

This is a more sophisticated attempt at modelling evacuation movement that allows for a more intelligent route to be adopted, instead of a 'dumb' waiting procedure being implemented. Local behaviour is essential in this respect as it allows small-scale navigation. Local behaviour has a number of aspects which will now be examined, and to which global behaviour defers in priority.

*Response Time*

This is a measure of the time occupants require before they positively react to the call for evacuation. An individual response time is part of the occupant attribute parameter set defined for a particular simulation scenario.

This effectively represents the cognitive processes highlighted by both Withey [184] and Sime [4] (see Chapter 2), in a single figure. Once the danger was perceived, people begin their evacuation procedure, following the global or local behavioural rules. To make the model more realistic, this may be overridden by the immediate presence of smoke/fire, which reduces their response time to zero, and therefore ‘encourages’ them to move off immediately.

This is an important consideration as it might be interpreted as covering a number of influential factors, and actions. A person’s pre-fire activity, reaction to the incident, and their interpretation of the environmental cues might all be claimed to be dealt with implicitly through this one value, as all of these would affect the person’s response time. However, this does not model the effect on the route choice of the individual of any of the above influences, and a more sophisticated mechanism would be required to accomplish this.

*Conflict Resolution*

If two or more individuals wish to move onto the same node, a conflict arises, which is resolved using the individuals’ personal traits. Given that the travel distances and speeds associated with each of the conflicting occupants are such that there is no clear winner, the outcome of a conflict depends on the *Drive* of each of the occupants.

The drive is a measure of the assertiveness of an occupant. The drives of the occupants involved in the conflict are compared to determine whether there are significant differences. If a significant difference exists, then the occupant with the greater drive will occupy the node. If there is no significant difference, the conflict is resolved randomly. Conflict resolution causes both the parties involved to incur a time penalty that effected their egress time.

The potential map, in conjunction with the global behaviour, are deterministic in nature,

so that the repetition of a simple simulation (one that does not involve people-people interactions, for instance), will generate identical results. However, once local behaviour is enacted, which is dependent on individual abilities and conflict resolution, both of which are probabilistic, different results may be produced from the same starting configuration.

It should be noted that through the resolution of the conflict, the individual is recognising the existence of other people, but only as objects with similar abilities, i.e. they hold no sociological significance to the individual involved.

#### *Overtaking*

This occurs because of the different movement rates available to individuals. Slower evacuees will block others, who will attempt to overtake by finding an adjacent unoccupied node. Local behaviour, in this respect, treats slower moving individuals as mobile obstacles, which need to be passed to return to the default global behaviour of evacuation.

#### *Perception of Fire Hazards*

As identified earlier, an occupant's response time can be overridden by the presence of fire or a cue indicating fire. These cues are represented by trigger thresholds, which when passed, represent enough evidence to indicate that action is required.

Presently, individuals will attempt to move through smoke, regardless of its density. This will affect the mobility and therefore the speed of the individual. The toxicity has a similar effect upon the occupant's progress.

#### *Exiting Procedure*

The exiting procedure is dependent on two factors: exit width and exit flow rate per unit width. The exit width determines the maximum number of people that can pass through the exit simultaneously. This in turn determines the number of nodes to be specified within the exit. The exit flow rate per unit width is used to determine the delay each occupant is likely to experience in passing through an exit. The exit flow rate is a user-defined adjustable parameter assigned to the exit. This can also be enforced by the user, guaranteeing that an exit has a maximum achievable flow rate. A number of well-accepted flow-rates are provided (including the flow rates of HMSO [185], Fruin [66],

Hankin [156], Polus [154]). These can then be implemented by the user to satisfy regulatory requirements or to guarantee previously generated empirical data.

Rather than defining a single value for the flow rate at each exit, a range of values may be used, so that at each exit an upper and lower limit is specified. Local behaviour rules remain operative within and around exits so that occupant-occupant interactions (such as conflict resolution) also influence the exiting procedure. As a result, arch-like structures are seen to form and collapse at crowded exits.

The model may also be used to *predict* the occupant flow rate through an exit during an evacuation. These calculations would be based on the delays that are incurred through occupant congestion and conflict resolution rather than imposing flow rates upon the occupant population.

#### *Staircase Movement*

The generation of staircases is a semi-automatic process, such that the user must define the location and some basic details. The geometry used can be a standard model, whereby the maximum amount of space available is utilised, or the effective width model [177], which takes into account the effects of handrails and body-sway, on the progression of occupants. Each riser is registered as a single node, thus the number of occupants on any one riser is dependent upon the width. Two behaviour regimes are available to the user, these are PACKED (where occupants are allowed to use any nodes but attempt to keep one riser spacing) and STAGGERED (where an attempt is made to maintain one riser spacing and one occupant per riser for narrow staircases, or keep one node spacing on risers in wide staircases [177]). Occupant travel speeds on stair nodes are based on data for Fruin [66].

#### *Performance*

Model run times for benchmark geometry have been generated as a basis for comparison with other evacuation models. The geometry consisted of a 50m x 50m structure with four 2m exits, one exit being located in each corner of the structure. The population consisted of a thousand randomly generated occupants, which were randomly distributed throughout the enclosure. On a Pentium II300MHz with 384 MB of ram, the simulation took 79 seconds in batch mode and 111 seconds to run in normal mode with full

graphical capabilities.

### *Validation*

The EXODUS suite of software has undergone several forms of validation including both qualitative and quantitative comparisons. This has involved direct comparison of model predictions with historic experimental data, comparisons of “blind” model predictions with experimental data and comparing the nature of predicted human behaviour with expectations.

First, wherever possible, model predictions have been quantitatively compared with data generated from *REPEATED* experimental trials. This has been done in an attempt to account for the variability in human behaviour. Without exception, this data has been generated from research in the aviation industry. This has been necessary, as data from repeated experimental trials only appears to be readily available from the aviation industry. While ideal for validating the airEXODUS model it is less than ideal for validating the buildingEXODUS model. However, both models are based on the same principles, with differences affecting the predictive capabilities of the models only occurring in the details of the behaviour sub-model. Comparisons of this type could be viewed as providing some justification for the buildingEXODUS methodology.

As a first attempt at this type of validation, a pre-release version of the airEXODUS model was compared against a selection of the Cranfield Trident Three experiments [186]. In this series of experiments, competitive evacuations were performed from a Trident Three aircraft cabin section, comprising 12 rows of seats organised six abreast and parted by a single aisle. The airEXODUS model was found to correctly predict the trends found in evacuation times [186].

More recently, predictions produced by airEXODUS Vβ1.0 were compared with a series of evacuation trials involving a B-737 mock-up [103]. The results shown in Figure 3-21 represent a subset of these trials. The straight lines that are imposed upon Figure 3-21 denote the outline of the experimental envelope. The envelope represents the outer bounds of the data generated by four repeated experimental evacuation trials. The stepped lines represent four airEXODUS Vβ1.0 predictions for this configuration. Clearly the airEXODUS results fall within the variation observed in the experiment [186].

The above cases represent comparisons of the airEXODUS model with historic data. In the second series of validation exercises, predictions from the airEXODUS model were compared with data generated from the certification trial for the B767-304ER aircraft (seating 351 passengers). However, the model predictions were performed and reports submitted to the UK CAA and USA FAA several weeks prior to the actual certification exercise taking place [186].

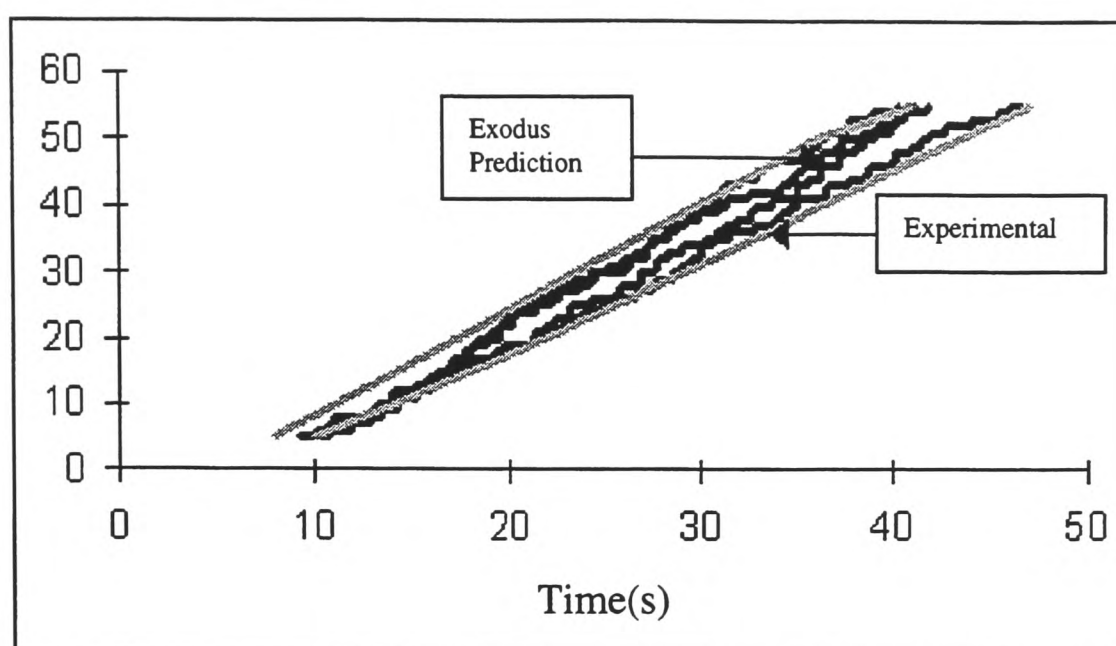


FIGURE 3-21: COMPARISON OF THE RESULTS OBTAINED FROM THE B737 SIMULATIONS AND THE AIRXODUS PREDICTIONS [103].

Unlike in the experimental evacuation trials, only a single certification trial is performed. As this does not allow for the variability in human performance a number of model predictions were performed to cater for a range of possible outcomes. Two types of scenario were investigated, each specific case within each scenario being repeated a number of times. The first scenario involved passengers heading towards the exit that is deemed optimal. A number of sub-optimal cases were also run. These cases give an indication of times that may be achieved if problems are encountered during the trial.

In order to specify various levels of sub-optimal performance a parameter was defined which enables the level of optimal performance in the simulations to be compared with the optimal performance achieved during the trial. Using this parameter it was determined that performance achieved by the passengers/crew/aircraft on the day was near optimal. The optimal airEXODUS predictions for the average evacuation time were within approximately 2% of the measured time [186]. Furthermore, general trends in passenger flow behaviour predicted by airEXODUS appear to have been corroborated by actual events, for instance, the passenger split within the cabin predicted by airEXODUS was achieved in the actual trial.



Some validation was also conducted by external researchers, through comparing the results of the model against the trial evacuation of a theatre [179]. A population of approximately 600 participants was arranged within the auditorium. The auditorium was completely evacuated in 5 minutes 20 seconds. This trial was used to validate the buildingEXODUS model as well as a number of other models [179]. During the cases, the researchers were entirely responsible for the definition of the parameters used. This would have certainly influenced the results produced. The evacuation was simulated as being finished at 5 minutes 35 seconds.

The third form of model validation concerns comparing the nature of predicted human behaviour with expectations. While this is only a qualitative form of validation, it is nevertheless important as it demonstrates that the behaviour built into the model is capable of producing realistic behavioural traits.

A number of such cases have been produced. One such case involves the evacuation of a hypothetical supermarket/restaurant complex [21]. The simulations were specifically designed to demonstrate the importance of including variations in travel speed and response time within the building population. The overall dimensions of the complex was 50m x 40m, with the restaurant area measuring 20m x 20m (see Figure 3-22). The geometry had four exits, all of which were located in the supermarket section.

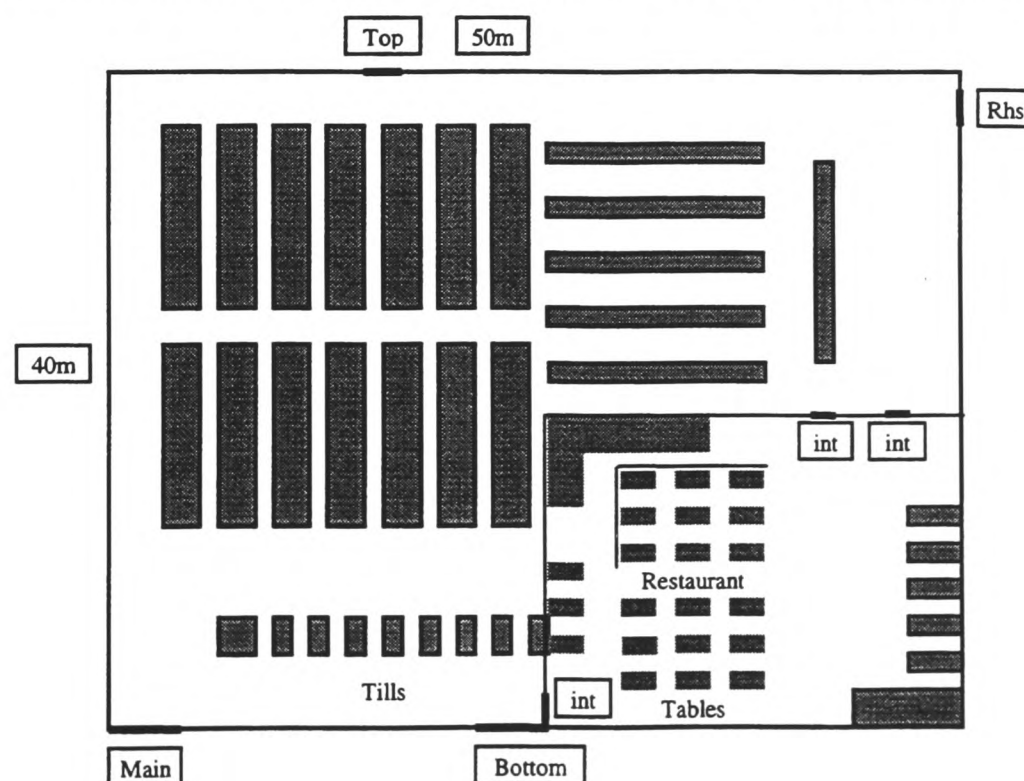


FIGURE 3-22 THE HYPOTHETICAL SUPERMARKET/RESTAURANT GEOMETRY. IN THIS GEOMETRY INTERNAL EXITS ARE DENOTED BY 'INT'.

Through the examination of occupant trajectories (see Figure 3-23), the behaviour



exhibited by several of the occupants can be examined. The figure clearly demonstrates the overtaking and route diverting capabilities of the population. For instance, occupant 1 started from within the rest-room and hence had a long response time, allowing little interaction with other occupants. Occupant 2 started in the restaurant area and had to go around immobile occupants on route to the exit, encountering a large amount of congestion. Occupant 3 started on the shop floor, and made their way around five slower stationary occupants. Also occupant 3 was forced to choose a route other than the most direct path (through the first till area) as it was blocked.

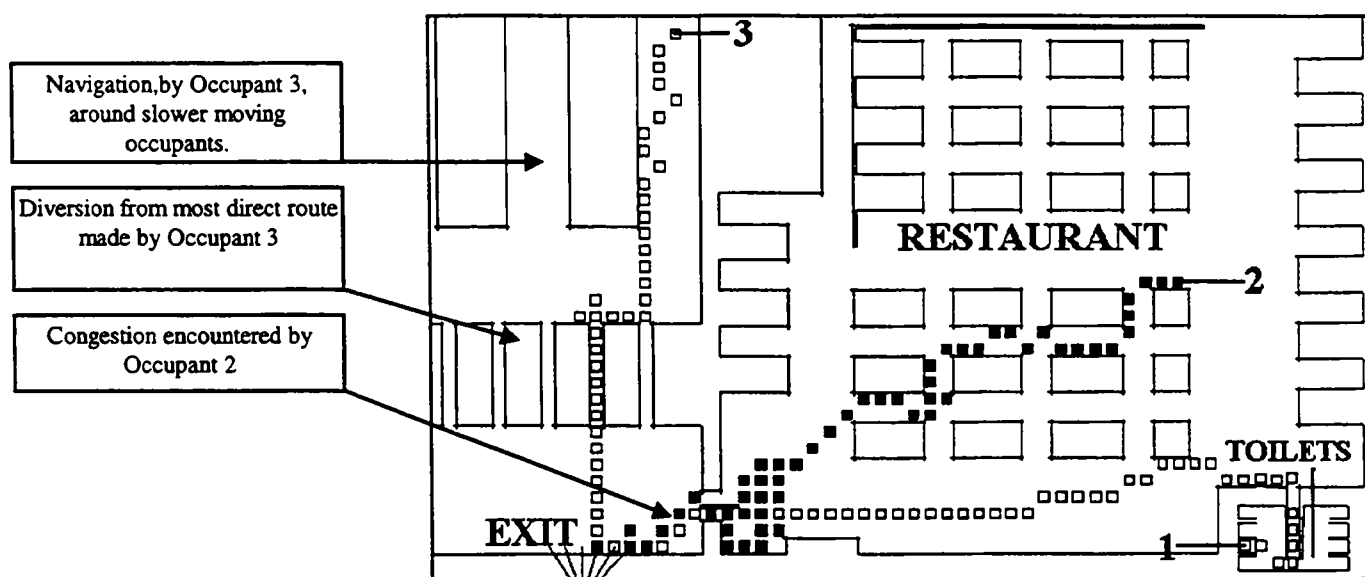


FIGURE 3-23: EXAMPLE PATHS TAKEN BY THREE OCCUPANTS TO EVACUATE THE SUPERMARKET/RESTAURANT GEOMETRY.

At present, the inclusion of behaviour which delays, or redirects egress, is seen as vital in accurately demonstrating the events of an evacuation [4,60,142]. buildingEXODUS has been developed to incorporate many of these characteristics and, due to the modularity of its design, will incorporate a number of the behavioural enhancements at present under development.

The buildingEXODUS model will be continually returned to during this dissertation, as it is used as a computational shell within which behavioural developments will be implemented and tested. This is due to reasons of practicality and of the relatively advanced stage of development of the model. However, it was felt necessary for the model to further validated, allowing a greater understanding of the progress made. This will addressed in Chapter 4.

## BFIRES-II [166]

B-FIRES II was originally designed at the NBS in 1977 to simulate the evacuation of health care facilities. It concentrates upon the occupant behaviour in response to the existence of a fire/smoke hazard.

It is a discrete time-based model that allows the occupant to respond according to a number of internal attributes and the information available to them from the environment.

B-FIRES II has been developed in FORTRAN-V, since 1977 and runs on the UNIVAC and INTERDATA computer systems. It requires the user to describe the simulation details through the use of data files that can, due to the detailed requirements, be relatively complex.

The occupant is seen as an *information-processing* agent who receives information from the surroundings, processes this data and then acts accordingly (see Figure 3-24). As Stahl states,

*“The response-generation capability of BFIRES is based upon an information processing explanation of human behaviour, and suggests that building occupants act in accordance with their perceptions of a constantly changing environment.” [166]*

This process occurs in time frames of 1.5 seconds. The occupant makes decisions concerning their path not only according to their present position and conditions but also in relation to their previous experiences within the evacuation. This information included data concerning the hazard, the geometry and other occupant's.

An example provided by Stahl is the ability of occupants to maximise distances to the fire threat and minimise the distance to a desired exit, given the appropriate knowledge. This response is selected from a number of dynamic program libraries that described occupant behaviour.

The occupants, which are defined individually, include a number of attributes, including *a role (such as a helper or a resident), a level of mobility, a co-ordinate*, denoting the exact position of the occupant and a number of other figures representing the occupant's

*“behavioural objectives, pre-dispositions and probabilities”.[166]*

No reference is made to the occupant's initial response to the evacuation, although the occupant may respond to the *immediate* threat of the hazard.

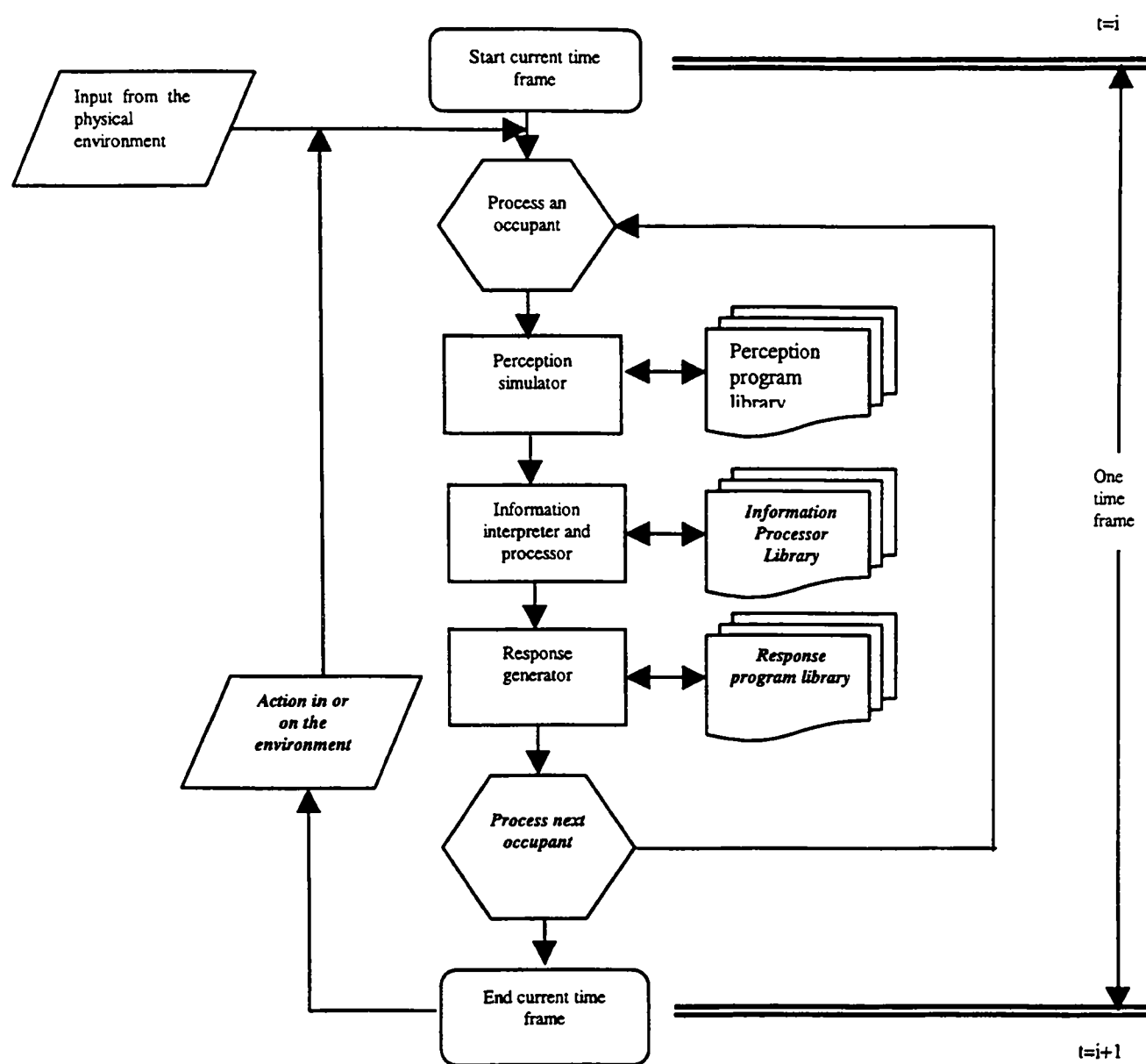


FIGURE 3-24: DESCRIPTION OF THE BFIRES II MODEL [166].

In effect, although a behavioural engine is in place, the user defines the probability of the occupant performing certain actions prior to the simulation. No description of the wayfinding algorithm is provided, although the maintenance of distances from certain objects suggests a distance mapping system of some kind.

The occupant behavioural features outlined by these probabilities include locating exits, occupant familiarity with the enclosure, exit manipulation and their environmental tolerance. It is not clear whether the mobility of the occupant is defined in relation to a scale or whether is automatically defined once the occupant has been labelled (such as being defined as 'non-ambulatory', for instance).

The geometry may consist of a number of separate compartments. No upper limit is provided upon the number of compartments. It can include a number of exits and safe refuges, the familiarity of which is local to the occupant. No explicit mention is made as to how the geometry is defined, although the occupant location is co-ordinate based,

suggesting a continuous description. The floor-plan may consist of free-space, exits and staircases. However, no mention is made of the model's capability of representing multi-storey structures, although it is assumed to exist due to the presence of staircases.

The occurrence of a hazard may also be represented within the model. The user defines the hazards initial position as well as the rate at which the fire and smoke spreads throughout the geometry. it is not clear as to the level of detail required for the hazard representation (toxins, etc.).

Once complete the simulation produces a number of statistics, including the number of occupants successfully evacuated, the 'escape score' [166], the (average) route length, the time frames spent by occupant in smoke-free/toxic environment and the number of non-ambulatory occupants evacuated through the provision of assistance by 'helpers'.

Some qualitative demonstration is provided concerning the flexibility of the behavioural model, involving a number of different enclosure representations and occupant populations. However, this is not compared against actual data. Some comparison is made concerning the impact of population density upon occupant walking speeds and the resultant flow rates generated. This is achieved through the use of simple corridor structures. The results produced were within the experimental comparisons used.

No indication is given concerning run times or the interface provided. It is assumed that given the relative age of the model that the system is based on a batch mode or text-based interface.

Overall, the BFIREs-II system has a relatively detailed representation of occupant behaviour, especially considering its age. However, the description provided is vague requiring a significant degree of interpretation. The model also requires significant validation to provide confidence in the accuracy of the quantitative aspects of the model and the qualitative assumptions of the model.

#### **FIRESCAP [49,50]**

FIRESCAP is a computer simulation model designed to represent relatively small numbers of occupants evacuating from simple geometries. It was developed at the University of Ohio, using the TurboBasic system. It was derived largely from the

creators extensive analysis of the Beverly Hills Supper Club incident [49,50,52], suggesting a simulation model that was based around the *social sciences* rather than one that is totally dependent upon physical considerations.

It provides a graphical representation of the simulation that is updated at each time frame. The simulation is updated in 2-second cycles allowing behaviour and environmental decisions to be adjusted. It produces a graphical data output relating to the progress of individuals, pairs, the competitiveness of the population and the number of occupants remaining in the room once the evacuation has been completed (see Figure 3-25).

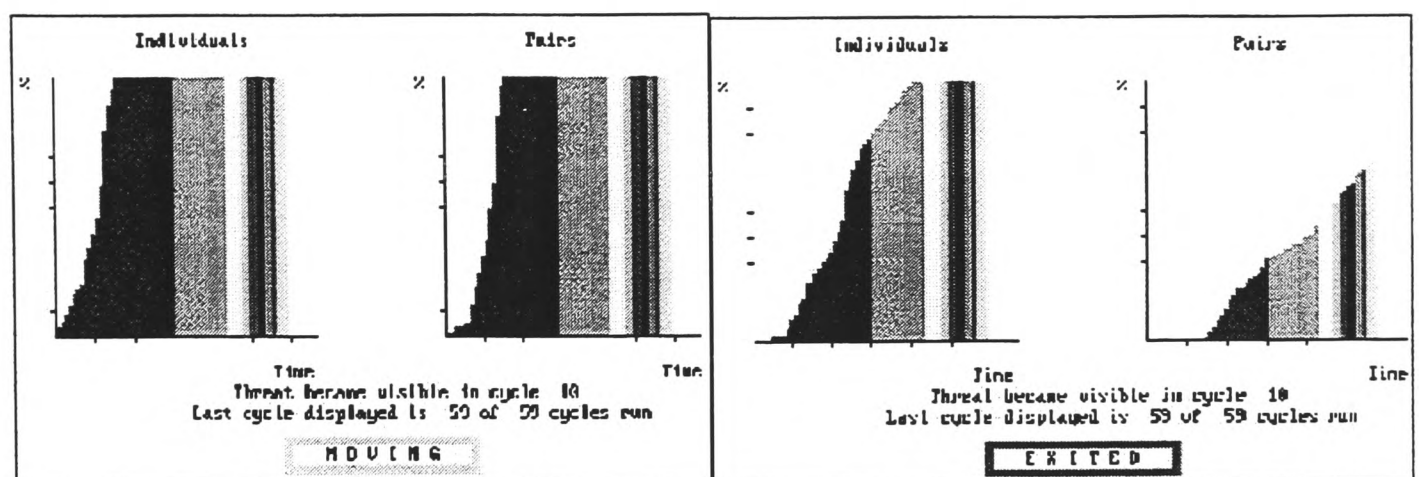


FIGURE 3-25: EXAMPLES OF THE GRAPHICAL OUTPUT OF THE MODEL

The geometry is formed from a mesh made up of  $1\text{m}^2$  squares. These can be occupied by up to a maximum of 2 ‘actors’ in the absence of a perceived threat and 8 ‘actors’ when there is a threat is evident, derived from the work of Pauls [99] and the national fire code. Therefore the size of the spaces does not alter, but the expected occupancy level is adjusted according to the perceived circumstances. This might be seen as an implicit attempt at representing the willingness on behalf of the occupants to accept more extreme conditions given the severity of the conditions.

The locations may attain a number of states. These include being *open* (the location being available), *blocked* (the location being unavailable) or *semi-blocked* (the location being available only at the beginning of a time frame).

The model is not simply based around social factors but also includes the environmental impact upon the occupant, albeit a slightly arbitrary representation. The fire threat is represented as an increasing index of severity between 1 and 100. The degree of physical threat is calculated according to

$$\Theta_t = \Theta_{t-1} \cdot \alpha \cdot e^{R \cdot \beta}$$

where  $\Theta_t$  is the physical threat at time frame,  $\alpha$  and  $\beta$  are parameters and  $R$  is a random number (0-1.0). Once the environment has been calculated as reaching 100, the conditions are considered untenable and any occupants remaining in the geometry are deemed to have succumbed.

Occupants within the structure are seen as individuals or are tied to another socially significant occupant, in a *dyad* [49,50]. Once formed these social bonds are assumed to be *unbreakable*, therefore forcing the occupants to maintain proximity throughout the evacuation.

Occupants are provided with a *perception* score between 0.5 and 1.5. This fluctuates according to the conditions. Once the score becomes greater than 1.0, the occupant is regarded as *aroused* and may then engage in competitive behaviour. This directly affects the resolution of conflicts over the desired location of the occupants.

If the occupant is part of a pair, they are still perceived as *individual* decision-making entities. Once decisions are arrived at, they are compared according to the '*deference characteristics*' of the individuals, reflecting the social standing of the individuals involved. This determines whether one of the occupants is willing to adopt the decision of the other member of the pair. Once the action is shared, the occupants move off. However, if one of the partners does not defer, the pair will not move off and the pair will continue to examine the decisions made.

These choices may alter, diverting the occupant away from their initial choice of exit. Occupants analyse their present course of action to determine whether, given the perceived conditions that they have enough time to evacuate. As the authors note,

*"Actors are continually calculating the difference between the perceived time available for exit and the perceived time need for exit through the currently intended exit" [49,50]*

The perceived time calculations are derived from the work of Sime. The path adopted towards the occupant's target is affected by the possibility of the surrounding crowd occupying possible locations and the extent of the physical threat. Therefore the occupants decision-making process is summarised by the creators, where

*"The model postulates that flight emerges over time as the selected response to a potential threat in an ambiguous situation. The response is neither instantaneous nor simply an aggregation of non-rational responses by individuals, as postulated by panic*

*models. Rather, we argue that the collective response is social, is guided by normative expectations and role demands, and usually occurs only after information is sought and ambiguous cues are assessed.” [49,50]*

Occupants have a number of attributes that are individually stored. These include

- whether the individual/pair is stationary, moving or exited
- whether the individual/pair is successfully evacuating
- the entrance used by the occupant/pair
- a perception score
- occupant speed
- choice of exit
- response time

The occupant’s decisions are based on physical and social evidence, according to the decision cycle. The likelihood of an occupant moving off in response to communication is linked to a dynamic ‘global probability’ that is calculated according to the existence of a visible physical threat. The probability of an occupant responding is also influenced by the number of other occupants responding, implicitly assumes communication, so that

*“The most important cues in the decision to exit are warnings from the staff and direct evidence of the severity of the fire, but the behaviour of others can also be a cue to the threat”[50]*

The occupant ‘s travel speed may take a number of values according to the population density and the surrounding conditions. These include

- a walking speed of 1.0 m/sec
- a fast walk speed of 1.5 m/s
- a run speed of 2.0 m/s

The occupant’s speed can be adapted at each time frame according to the conditions perceived.

Actors are most likely to adopt the exit through which they entered reflecting the work of Sime [4] on familiarity. The path adopted by the occupants is not calculated deterministically, but are established through a chain of events according to the locations adopted by the occupant.

Occupants are able to adopt two separate styles of behaviour; *competitive* and *co-operative* (the default position). The movement between these two states is a direct consequence of the occupant’s analysis of the severity of the situation and the numbers of competitive and co-operative actors nearby. Competitive flight extends to pushing and does not include unregulated movement where social ties are assumed to have dissolved. The actors are initially placed randomly throughout the geometry. When a location



contains more potential occupants than is permitted, the conflict between occupants must be resolved. This is achieved according to the behavioural status of the occupant and whether they form a pair. Therefore a priority hierarchy exists as follows

- competitive individuals
- competitive pairs
- co-operative individuals
- co-operative pairs

Those who fail to move are returned to their previous position.

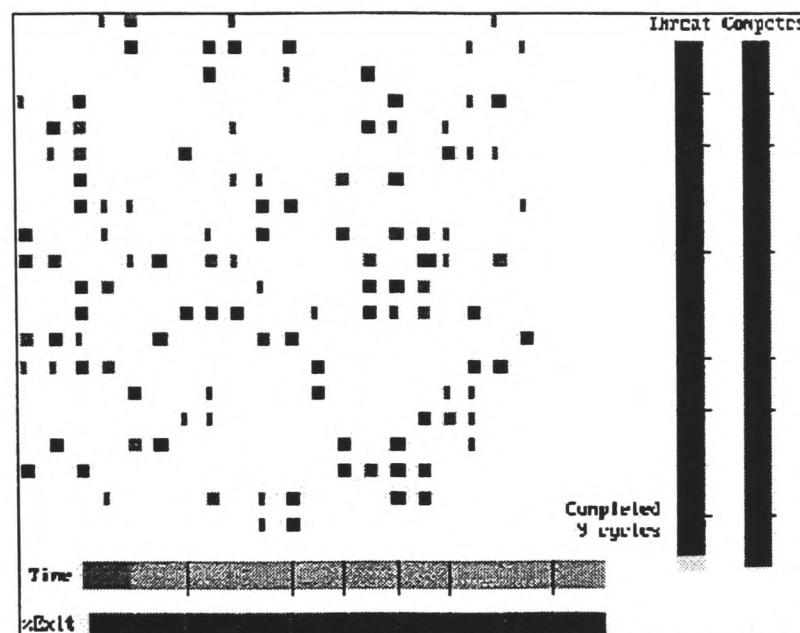


FIGURE 3-26: GRAPHICAL INTERFACE PROVIDED BY THE FIRESCAP MODEL

A single run of a simulation takes approximately 90 seconds on PC, which has a specification of 486DX2-66 or 270 seconds on PC 386DX-20. The system allows batch processing that reduces the time taken, so that 10 simulations in batch mode take 180 sec (486 DX-2) and 900 seconds (386DX-20). Each run will produce different results as the calculations are based around the Monte-Carlo technique.

A degree of sensitivity analysis has been conducted concerning the ability of the model to represent particular activities and their impact upon eventual evacuation times [49,50]. These include the transfer of information in relation to the existence and use of exits, the perceived time of egress and subsequent occupant decisions to initiate evacuation. The model was demonstrated as being sensitive to all of these factors. However, except for reference the Beverly Hills Supper Club incident little comparison with actual occupant behaviour was made.

The model presents a relatively advanced attempt at representing occupant behaviour within a difficult environment. It represents a number of social characteristics, including a relatively advanced representation of the social affiliation of the occupant population. It does require a degree of development concerning the interface and the capability of the



model to cope with more complex geometries.

A)IV)ARTIFICIAL INTELLIGENCE BASED BEHAVIOURAL MODELS.{EG[18-20], O-O[168], V[46,47]}

#### EGRESS [18-20]

EGRESS[18-20] is a PC-based evacuation model, designed at AEA services, which uses artificial intelligence techniques to evaluate the decision-making process during the evacuation of single- or multi-storey structures. Ketchell et al claim to use cellular automata to determine decisions on a local basis, which they describe as

*“The technique used is known as ‘cellular automata’, in which a floor area is divided into cells, which might be occupied or unoccupied, and for which transition rules exist which govern the motion of the automata (people) between the cells.” [18]*

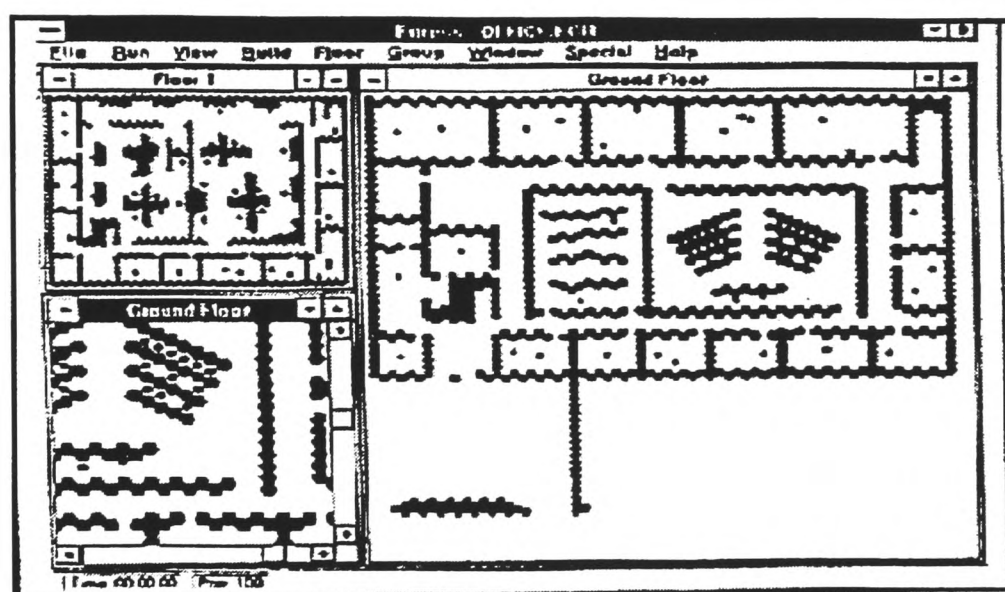


FIGURE 3-27: EGRESS SCREEN DUMP CLEARLY SHOWING THE HEXAGONAL NODE STRUCTURE.[18]

The structure is represented by a hexagonal grid system, enabling a refinement in the angle of movement, over square nodes (see Figure 3-27). Each of these cells represents enough room for one person, although the actual size of these hexagonal cells is not specified.

The movement from one node to another is separated into primary and secondary movements. Primary movements are from the centre of the occupied plaque to one of the three plaquettes in front of the occupant. All other movements (secondary movements) are made up from the occupant rotating and using a combination of primary movements [20]. This encourages occupants to move in an unnatural 'zigzagging' motion.

The density of the surrounding crowd governs the speed of movement between nodes. The data used to generate this movement is chosen to represent a number of crowd density functions, through the averaging of different collected data. The work of Fruin

[66] , Pauls [177] and Predtechinskii and Milinskii [150] is discussed although there is no explicit link made by the developers between this discussion and the movement model implemented, or whether this model includes the stairway movement identified by Pauls[177].

Decisions are achieved by comparing intermediate and long-term goals with the present surroundings in a feedback loop, with the direction of movement based on a probabilistic rule-based system. A graphical description of this model is shown in Figure 3-28. There exist a number of ways in which the occupants might complete a task or arrive at a location. Over a number of experimental runs, the developers designed occupant behaviour to vary according to a normal distribution. The choices that occupants make at each plaque are therefore governed by this distribution, which then determine their next immediate short-term goal.

Stimuli are perceived by people, who then comprehend these perceptions through the use of a script system that is based on occupant expectations. Scripts determine behaviour, by identifying goals, which in turn are determined by specific stimuli, similar to the BGRAF [14] model. This behaviour effects stimuli and therefore expectations, forming the feedback loop in Figure 3-28. The developers highlight the advantage of such a method as,

*“It allows a simple interface to modelling behaviour since individuals, or groups, can easily be identified and treated in a different way. This is of vital importance since it is apparent from accident reports that there is not just one pattern of behaviour for all people, but a range of such behaviour.”[18]*

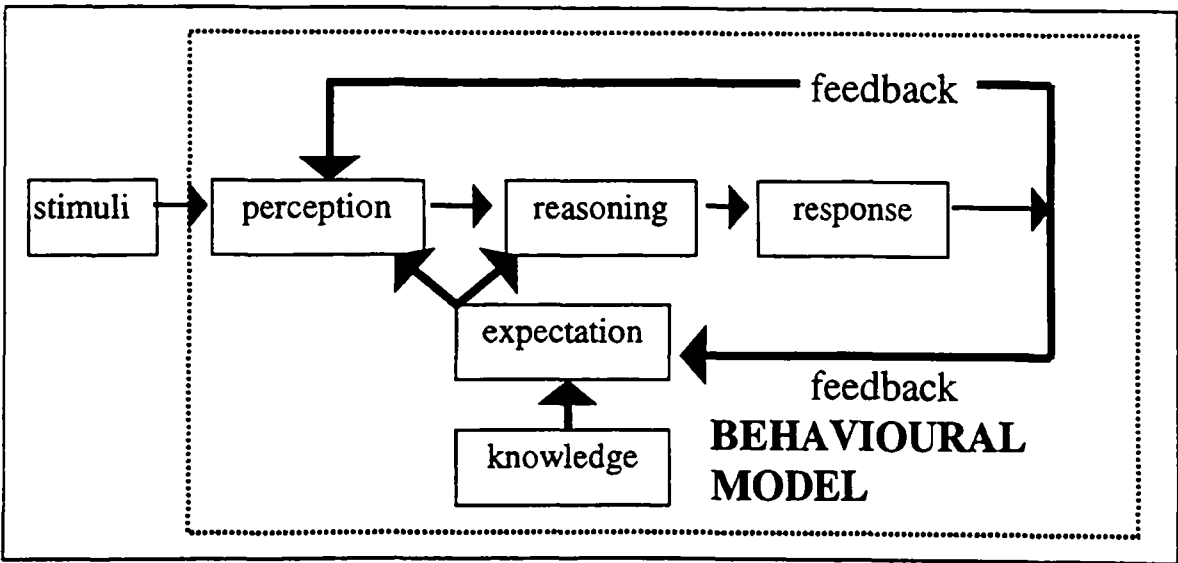


FIGURE 3-28: OVERVIEW OF EGRESS BEHAVIOURAL MODEL.[18]

Little detail was given on this technique, providing no information concerning types of behaviour which could be covered in such a model, other than to say that different

groups may be defined, each with their own movement speeds. These different groups may then be assigned different goals [19]. EGRESS is not capable of representing the hazard scenario. The developers identify that,

*“EGRESS is designed to be able to look at a hazard progression scenario, but it is not designed to calculate what that scenario is.”[18]*

that suggests the external nature of the hazard generation. EGRESS is therefore reliant upon the accuracy of another model, whose information it imports to determine the blockage of egress routes.

Theoretically, a large variety of activities could be simulated through the use of cellular automata, as individuals could implement scripts taken from an external library. However, the methods employed were not identified. The developers explain their vagueness by pointing out that the data on movement has an uncertainty about it, and that models might still be of use if they present a guide to outcomes, instead of an exact answer.

The developers attempted to provide validation for the flow produced by the model through openings, via comparison with empirical data determined using Pauls [177] flow relationships. The maximum possible flow generated by EGRESS (0.49 people/sec./cell width) was 29% lower than the corridor flow rate produced by Pauls (0.63 people/sec./cell width) and 40% below the door flow rate produced by Pauls (0.68 people/sec./cell width). When the calibration of door flow rates was extended to be included in a sample geometry, flow rates of 60% higher than those expected were generated. This was accounted for by the step change in density between the inside of the door during the simulation and that outside the door, which was zero, as it was effectively outside of the simulation. In real-life comparison the movement through the door would not have been subjected to such a discontinuous change [20].

Further attempts at validation were made through the comparison with the simulated evacuations of the Tsukuba Expo '85 Pavilions, involving a 424 seat pavilion (which was assumed to be fully occupied), and a 500 seat pavilion (which had 450 occupants) [20]. The results provided, indicated an agreement between predicted and actual evacuation of within  $\pm 20\%$  (see Table 3-4 and Table 3-5). When simulating Pavilion 1

(see Table 3-4), EGRESS correctly identified the most popular routes of exit, but produced large inaccuracies in evacuation times, due to the doorway problems highlighted earlier. When simulating Pavilion 2 (see Table 3-5), the routes chosen by the occupants were less appropriate, forcing a high degree of crowding, causing longer than expected evacuation times. This identifies an underlying unreliability in the EGRESS movement model. The developers concluded,

*“Given the complexity of the evacuations, this level of agreement is very encouraging.”[19]*

TABLE 3-4: PAVILION 1 (500 SEATS) EVACUATION TIMES MODELLED BY EGRESS.[20]

Observed Evacuation times[s]		Predicted Evac. Times[s] (95% Confidence Limit)	
Mean	S.Dev	Mean	S.Dev
160		129-136	3.4-9.1

TABLE 3-5: PAVILION 2 (424 SEATS) EVACUATION TIMES MODELLED BY EGRESS.[20]

Observed Evacuation times[s]		Predicted Evac. Times [s] (.95% Confidence Limit)	
Mean	S.Dev	Mean	S.Dev
66	6.0	83-88	2.0-5.4

A comparison of simulation performance was also carried out against the Trident evacuation drills [142], as highlighted in the previous section referring to EXODUS. When using the Type II exit as comparison, the results generated were within 30% of the expected results (see Table 3-6).

TABLE 3-6:TYPE II EVACUATION, WITH VARIATION OF BULKHEAD GAP[20].

Bulkhead [m]	[cells]	Observed Evacuation times[s]		Predicted Evac. Times[s] 95%	
		Mean	S.Dev	Mean	S.Dev
0.5	1	25	2.0	32-34	1.7-2.7
0.9	2	18	3.4	29-31	2.2-3.3

The comparison suffered when the exit (Type III) was of a non-standard geometry (1.05 metres in height). In this case the model predicted times up to 50% faster than those observed (see Table 3-7).

TABLE 3-7:TRIDENT EVACUATION, EXAMINING EXIT HEIGHT 1.05M OF TYPE III EXIT. TIMES ARE FOR THE 30TH PERSON TO EVACUATE.[20]

Observed Evacuation times[s]		Predicted Evac. Times.95% Confidence Limit	
Mean	S.Dev	Mean	S.Dev
53.7	8.2	24.3-25.5	1.8-2.7

This led the developers to concede that,

*“Further work is required to produce realistic flow rates through openings of unusual geometry.”[20]*

This series of validations indicate that although EGRESS allows some flexibility in the handling of occupant behaviour, the movement model implemented requires refinement, especially in relation to doorways.

Other validation attempts were made, including the evacuation of a double-decker bus [20], highlighting the developer's belief that this is a general purpose model. However, as previously mentioned, the inaccuracies evident in the results indicate that the model can not at present cope with structure specific behaviour.

Recently a number of behavioural advances have been demonstrated by the creators of the EGRESS model including the representation of group behaviour, the reassignment of targets, delay areas and more complex means to represent occupant familiarity. However, no published literature is available by which to analyse these developments [189].

#### **VEGAS[46-47]**

The Virtual Egress Analysis Simulation [46-47] utilises recent developments in virtual reality (VR) techniques in an attempt to model egress patterns. The system, developed at Colt VR Ltd., is intended to be used to represent a number of enclosures, including single- and multi-storey structures, within the Superscape VR environment. It is intended to be run on the 486 PC, with SVGA compatibility, or better.

Unlike many of the models discussed, Vegas does not provide an occupant wayfinding capability, but instead relies upon the user to provide a route for each occupant.

The individual occupant is represented as an 'intelligent' object within the VR environment. As Still claimed, Vegas

*"Allows the engineer to enter a computer simulation of his design, experience an event, use this insight to improve the layout, and test various contingency arrangements."*[46]

The abilities of the occupant are constant as are the dimensions of all the occupants. Behaviour is seen as a chaotic system, which presents immense computation problems. Using Complexity Theory (or Anti-Chaos), the developer claims that it models human behaviour according to a small number of simple variables (in this case objective, constraint, and motivation), which gives rise to immense complexity. The result is

*"A group function which exhibits emergent behaviour, i.e. the characters are programmed with one kind of behaviour, such that the group behaviour cannot be reduced back-down to the behaviour of the individual."*[47]

Although this is claimed to be implemented, it is not immediately apparent as to how this is achieved, apart from combining several variables that are acted upon by functions, causing a level of complexity. The exact methods of applying ‘anti-chaos’ are not specified.

The developer claims that the Vegas behavioural model includes group behaviour, the effect of smoke, fire and toxic gases, alarm awareness, simplistic communication, and leadership. However, none of these factors have been calibrated using real-life data.

Through the adoption of complexity theory, the model incorporates behavioural rules dependent upon,

- An Objective, such as an attempt to try and leave the system.
- A set of Constraints, such as an attempt maintain a minimum distance between yourself and other individuals
- A Motivation, such as an attempt to maintain optimum velocity.

The developers claim to use a CFD model to generate the hazard event, but very little information is provided on this subject.

Decisions are made on the basis of a trigger system, allowing choices to be made on a discrete basis, which is claimed to be in real-time. Movement speeds are not calculated using the normal speed/density curves, but are instead based upon ‘proximity logic’ that relies upon the exact location of the occupant in relation to the other objects involved in the simulation. This ‘proximity logic’ includes a flocking algorithm which caused individuals to congregate, depending on their position. The sophistication of this algorithm was not discussed.

The model does include a form of effective width model, although this has not been calibrated effectively with real-life data.

The route finding mechanism is capable of working at high degrees of accuracy, with the drawback that an enormous amount of user input is required to generate any complex evacuation route. Every change of direction is required, with mistakes being punished by improbable outcomes, such as being trapped behind an obstacle until incapacitation. The

high-level of user input needed to generate the occupant movement is prohibitive, and requires a level of user- expertise that the average user might not possess.

At the time of writing, it is not certain whether the VEGAS model is still available.

#### **OBJECT-ORIENTED SYSTEM[168]**

Ebihara, Ohtsuli and Iwaki[168] have developed an object-oriented system using SmallTalk-80, designed specifically to represent earthquakes and fire threats. The model is comprised of 3 separate modules: the *space* model, the *scenario* model and the *human* model (see Figure 3-29). Each of these will be addressed separately.

The *space model* uses a network system to represent the geometry. This may include staircases, passages and free spaces and describe represent multi-story structures. Each node possesses a number of attributes including the location, the lighting level, fire/smoke level and obstruction information. This information can be assessed when an occupant when an occupant is located on or adjacent to a node. The nodes may be grouped to create areas of a certain effect. No mention is made concerning how this information is entered into the system by the user.

The *scenario model* can include power failure and the occurrence of fire and smoke, all of which might follow the occurrence of an earthquake. These events may change throughout the scenario. The simulation is split into simulation steps, although the exact length of each step is not defined.

The occupant comprises of a number of attributes including the *walking speed*, a *memory*, the *psychological condition* of the occupant and *information provided by the adjacent nodes*. The occupants may be gathered together in groups to simplify the evacuation process.

The psychological condition of the occupant determines the order that inferences are made from a knowledge-base system. The inferences are separated into:

- The current information on the surrounding nodes
- The current direction of travel
- The memory of paths along which people can evacuate

The exact order in which these are implemented is dependent upon the '*panic ratio*' of

the occupant, which is directly related to the occupant’s psychological condition. When relatively calm, the occupant follows the priority outlined (i.e. starting with step one and finishing with step three). This is therefore assumed to be the most *considered* action possible. Under extreme conditions, when the occupant is assumed to have a higher ‘panic ratio’, the order of priority changes to step 2, step 1 and then step 3. *The modellers therefore explicitly recognise a dichotomy between behaviour according to the hazard posed by the environment.*

Navigation is maintained according to the nearest available exit, staircase or guide-light. Again these are prioritised in the order presented. The occupant (or group of occupants) can navigate according to blockages and attempt to maintain a distance from hazards within the enclosure.

A demonstration is described showing 200 occupants (that are represented in groups of five) evacuating from a 2 floor multi- exit structure. The occupants are shown *redirecting* according to the environment, which is demonstrated as being dynamic. No details are provided concerning the small-scale behaviour or of the quantitative accuracy of the model.

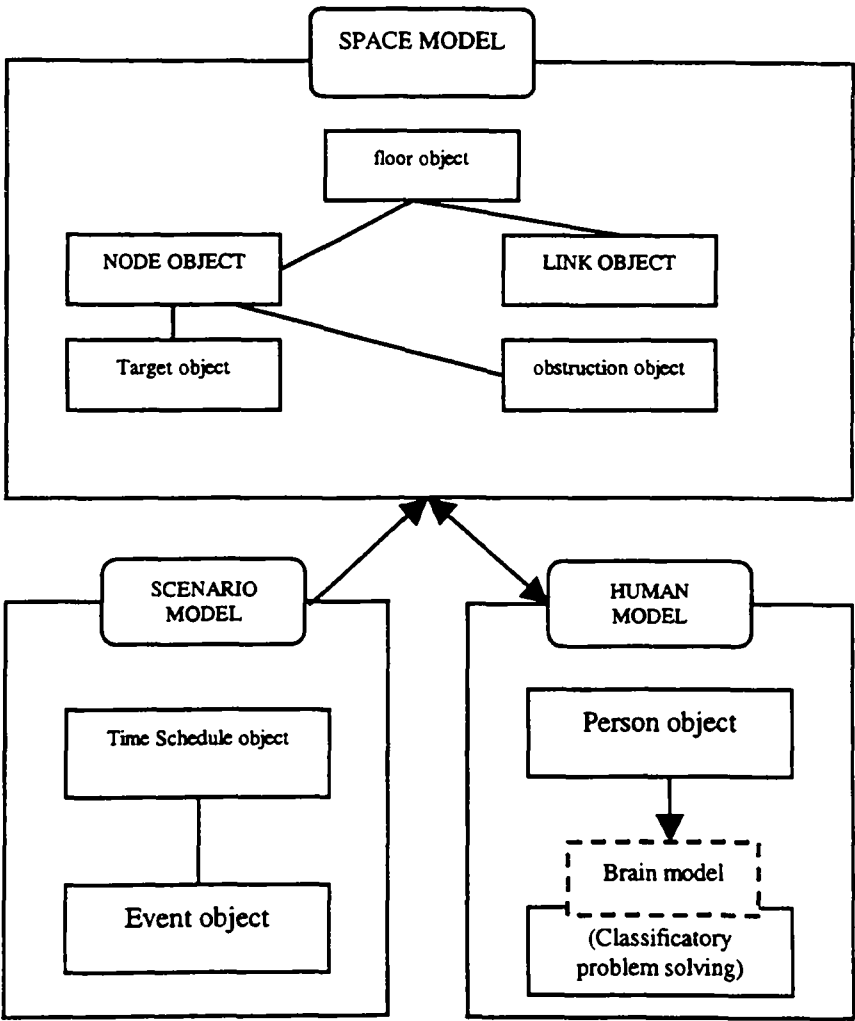


FIGURE 3-29: INTERACTION OF SUB-MODELS [168].



Although a complex behavioural model is apparent, the ambiguity of the description prevents detailed analysis. It lacks detailed validation and relies on an outmoded view of occupants automatically resorting to flight behaviour under high degree of stress.

### 3.2 OPTIMISATION MODELS{ EV[30,31], TF[45] }

In this section *Optimisation* models will be discussed. All of the optimisation models utilise a coarse network model to describe space and employ a global perspective to describe the population. The discussion thus focuses on the manner in which behaviour is described.

#### 3.21 COARSE NETWORK{ EV[30,31], TF[45] }

##### A)GLOBAL PERSPECTIVE{ EV[30,31], TF[45] }

##### I) NO BEHAVIOURAL RULES APPLIED. {EV[30,31] }

##### EVACNET+[30,31]

EVACNET+[30,31], developed by the University of Florida, is a coarse network model, where nodes represent building components, and arcs represent the passageways between them. It is developed from a modification of a traffic simulation model developed by the authors. Initially, the user supplies this node information and information about the initial distribution of occupants. EVACNET+ is written in FORTRAN for the PC, and is capable of analysing multi-storey buildings.

The program optimises evacuation plans for structures designed by the user using linear programming techniques, and then outputs flow rates, the length of queues, and the mean waiting times.

The nodes require two types of input: the node capacity and the initial contents of the node. If the contents of a node are greater than the capacity, then capacity algorithms, derived from queuing theory, are employed, to resolve the over-population. The arcs work on a flow capacity basis, which acts as an upper limit on the number of people who may cross the arc at any one time, and which remains constant throughout the simulation.

The model makes calculations using a default time period of 5 seconds. It uses a 'capacitated network flow algorithm' to determine the optimal evacuation plan. The arcs require three types of input; the level of service [66], the effective width of the arc [177] , and the travel speeds at that location and the distance that the arc represents which

remain constant throughout the simulation. EVACNET+ makes no attempt to model the spread smoke and fire, and implements no behavioural model. As such, it is a simplistic attempt at modelling evacuation, as the only behaviour it appears to include concerns the direct movement of people towards an exit. Even so, this process can involve a large amount of data input for the evacuation of a complex enclosure.

The developers claim to be able to simulate a variety of different forms of enclosure, but this is dependent upon the user supplying correct data, and not on an internal model.

EVACNET+ assumes a global or system viewpoint, allowing the system self-organisation, i.e. the capability to have a complete information set, and therefore utilise this in an attempt to minimise egress times. The developers recognise this weakness, and attempt to explain this in the following way,

*“In an actual evacuation, it is more likely that evacuees will view an evacuation from their individual perspectives. One major use of EVACNET+ can be to inform potential evacuees and/or the floor wardens of globally optimal building evacuation plans.” [30]*

This relies on the false premise that by adopting the system viewpoint and ignoring individual motives, that this might provide an accurate representation of egress patterns. This may be better founded on an evacuation system that more accurately predicts the effects of individuals.

The output provided by EVACNET+, reflects the global view of the population and the coarse geometry network. Therefore the output concerns nodal populations, and cannot therefore be specified for individuals. It should also be realised that the queuing procedure concerns the movement of nodal populations, and not the more sophisticated queue formations that are visible in real-life scenarios.

Recently, a revised interface has been created for EVACNET+, which makes the system accessible under PC-Windows. The revised interface has not introduced any fundamental changes to the model structure or capabilities [31].

A general problem with this type of system is that it portrays the scenario as a network problem, rather than an evacuation problem represented by a network, and makes no reference to behaviour in any serious manner. However, EVACNET+ might be of some use in providing benchmark evacuation times, for use in the comparison of different

structures.

Johnson et al [189] provide a validation test for the EVACNET+ system through their comparison of the results produced through the system and an actual evacuation of 1014 unsuspecting occupants from the National Gallery of Victoria. The evacuation took place on a Sunday when the gallery was usually heavily populated. The comparison is slightly biased as information which might not have been known prior to the evacuation (e.g. the fact that an exit was completely ignored, the return of a number of occupants back into the structure, and the under-use of an exit), was entered into the simulation, therefore making the results more accurate than they might have been (see Table 3-8). When examining these results, it should be remembered that EVACNET+ produces optimal evacuation times, and therefore the over-estimation of the gallery evacuation times, is a significant error.

TABLE 3-8: COMPARISON OF ACTUAL EVACUATION TIMES WITH EVACNET+ PREDICTIONS.[189]

Exit name	Evacuation Time(sec)	EVACNET+ Time(sec)
A	420	424
B	420	424
C	480	521
D	480	512
Total Evac.Time	480	521

Finally, no information was provided concerning the run-time of the model.

**A)II)FUNCTIONAL ANALOGY BASED MODEL{TF[45] }  
FLUID MODEL[45]**

This is a PC-based coarse network model that assumes that evacuees move in a hydraulic fashion. The developers claim that an attempt to accurately model the majority of egress behaviours would be prohibitively difficult. Hence, the population is assumed to be homogenous, and move as a fluid in each space element. The population is uniformly distributed around the structure, although no justification is provided for this action. The space elements can be rooms, paths, stairs, vestibules, halls, and refuges. The model does not distinguish between movement across nodes, and movement between nodes, but instead relies upon the user defining the node/arc width to determine movement speed, supplying no internal model. This provides a method to distinguish between horizontal and stairway movement, but is completely reliant upon the user having the appropriate knowledge of population movement. The model is designed to cope with low-risk situations, where the effects of the environment are minimal, and therefore does

not include a hazard model, and may explain its lack of behavioural sophistication.

While the user has the ability to set delay times, as all the evacuees are members of an homogenous population, they all assume the same delay times.

Within the model, evacuees may approach an exit in two manners. If obstacles are present, an L-shaped approach is used, governed by the following equations,

$$P = \frac{\rho(vt)^2/2}{\rho(a^2/2 + a(vt-a))} \quad (0 < t \leq (a/v)) \quad (36)$$

$$P = \frac{\rho(a^2/2 + a(vt-a))}{\rho(ab - ((a+b-vt)^2)/2)} \quad ((a/v) < t \leq (b/v)) \quad (37)$$

$$P = \frac{\rho(ab - ((a+b-vt)^2)/2)}{\rho(ab - ((a+b-vt)^2)/2)} \quad ((b/v) < t \leq (a+b)/v), \quad (38)$$

where  $a$  is the short side of the room,  $b$  the long side (both in metres),  $t$  is the time lapse (in seconds),  $v$  is the walking speed(m/s),  $\rho$  is the population density (people/m<sup>2</sup>), and  $P$  is the number of people arriving at a particular exit at time  $t$ .

There is no method specified, to generate or locate obstacles. The equations attempt to account for the existence of obstacles by relating the delay in exiting to the presence of obstacles rather than detailing the effect obstacles have on movement.

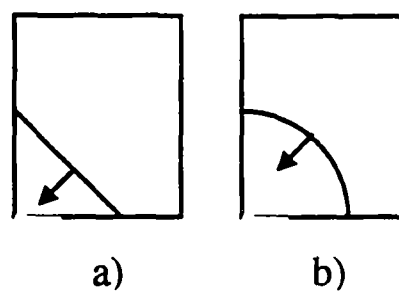


FIGURE 3-30: THE CATCHMENT AREA FOR THE L-SHAPED APPROACH IS SHOWN IN A), WHEREAS THE CATCHMENT AREA OF THE CENTRIPETAL APPROACH IS SHOWN IN B). THESE ARE EFFECTIVE AT A SPECIFIC TIME, AND THAT PROPORTION OF THE POPULATION CONSIDERED TO BE WITHIN THIS AREA AT THIS TIME, WILL EXIT.

THIS HIGHLIGHTS THE IMPORTANCE TO THE MODEL OF THE DISTRIBUTED POPULATION.[45]

If there are no obstacles present in the room, a 'centripetal' approach is used, where movement is governed by a similar set of equations, except incorporating trigonometric functions. It should be remembered that these equations effect the population and not the individual occupants. In this fashion, the proportion of the population within a node, effected by the calculated catchment area (see Figure 3-30 and Figure 3-31), will exit in the allotted time. This is dependent upon the population being evenly distributed throughout the nodes. The developer provides no evidence of the calibration of these equations with real-life data.

Exit choice is based on the assumption that individuals will choose the quickest option. The model simulates this by allowing the system to calculate this fact, and redistribute the individuals accordingly, allowing the evacuation system the emergent property of self-organisation. It also treats each compartment as having a single exit, simplifying the shortest route calculation. If a compartment has multiple exits, it will be broken down into smaller compartments. The only other behavioural consideration of note, is that individuals are assumed to

*“proceed orderly toward the exit without passing over or going backwards.”*[45]

The developers of this model make an initial assumption that individuals behave as a collective or ensemble during an evacuation without justifying such a claim, and then proceed to create the model on this basis. This approach suffers from the previously highlighted disadvantages of coarse networks, and the application of the global perspective.

The developers carried some validation tests based on data obtained during the Tsukuba International Expo, 1985 [45].

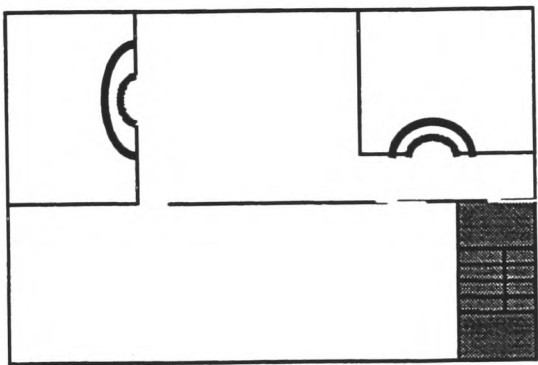


FIGURE 3-31: THE PROGRESSION OF THE CATCHMENT AREA DURING AN EVACUATION. THE GREY PARABOLAS INDICATE THE CATCHMENT AREA AFTER T TIME UNITS, WHILE THE BLACK PARABOLA REPRESENTS THE CATCHMENT AREA AFTER T+1 TIME UNITS.[45]

This concern the time it took individuals to evacuate the seven pavilions used in the exposition. Table 3-9, displays the results, with two attempts at predicting the egress times, initially enforcing L-shaped movement (case (a)), and then enforcing centripetal approaches (case(b))(see Figure 3-30).

TABLE 3-9: RESULTS OF VALIDATION TEST FOR FLUID MODEL.[45]

Pavilion No.	Egress Times (secs)	Avg (secs)	Estimated (a)(secs)	diff(%)	Estimated (b)(secs)	diff(%)
1	61,71,75,60,64	66	52	21	62	6.3
2	174,175	175	137	21	275	57.6
3	71,80,77,78,79	77	50	35	76	1.3
4	94,111,102	99	72	27	89	9.9
5	70,123,84,77	89	34	61	58	34.5
6	160,152,166,157	159	100	37	107	32
7	148,118,130,121,131	130	70	46	88	32

One of the explanations given for the apparent discrepancies was that the conditions surrounding the test were not “emergent”, and that it was raining, encouraging people not to leave the building, indicating a lack of robustness in the system.

### 3.3 RISK ASSESSMENT MODELS{ C[15,16], WO[48] }

In this section the *Risk Assessment* models are examined. As all the models utilise the coarse network approach the discussion focuses on the manner in which the population is specified, either using the a) Global perspective or b) the Individual perspective. Finally, the models are further subdivided according to the manner in which they include behaviour.

#### A) GLOBAL PERSPECTIVE {WO[48] }

##### A)I) IMPLICIT BEHAVIOURAL MODEL {WO[48] }

##### WAYOUT[48]

WAYOUT was created at the Australian Commonwealth Scientific and Industrial Research Organisation, to model merging traffic flow using a PC-Windows based environment. It is part of the FIRECALC 3.0 fire safety-engineering package capable of representing single- or multi-storey structures. Similar to EXIT89 [34,35] , WAYOUT is based on speed data collected by Predtechenskii and Milinskii [150], with flow density defined as

$$D=Nf/wL, \quad (39)$$

where  $N$  represents the number of people,  $f$ , the horizontal projection of person (assumed to be 0.113m),  $w$ , width, and  $L$ , the length of the stream, with  $D$  having a maximum density of 0.92. When calculating stair movement, the stairs are assumed to be of standard steepness. Therefore, riser/tread size variations are not considered in the model.

WAYOUT treats the structure as a network, which can consist of up to 200 rooms. WAYOUT separates structures into twigs, which are compartments of constant width. Traffic enters a twig through an entrance door, whose rate of flow is denoted by the number of streams at that point. People move in packs through streams into twigs, whose representative function  $\text{Twig}()$ , acts recursively inside the model. When a new pack enters a twig, velocity falls due to an increase in density, using the following equation to determine the flow,  $F$ ,

$$F = \frac{vDw}{f} (\text{persons/min}) \quad (40)$$

where  $v$  is the traffic speed. This equation is based upon the work of Predtechenskii and Milinskii [150].

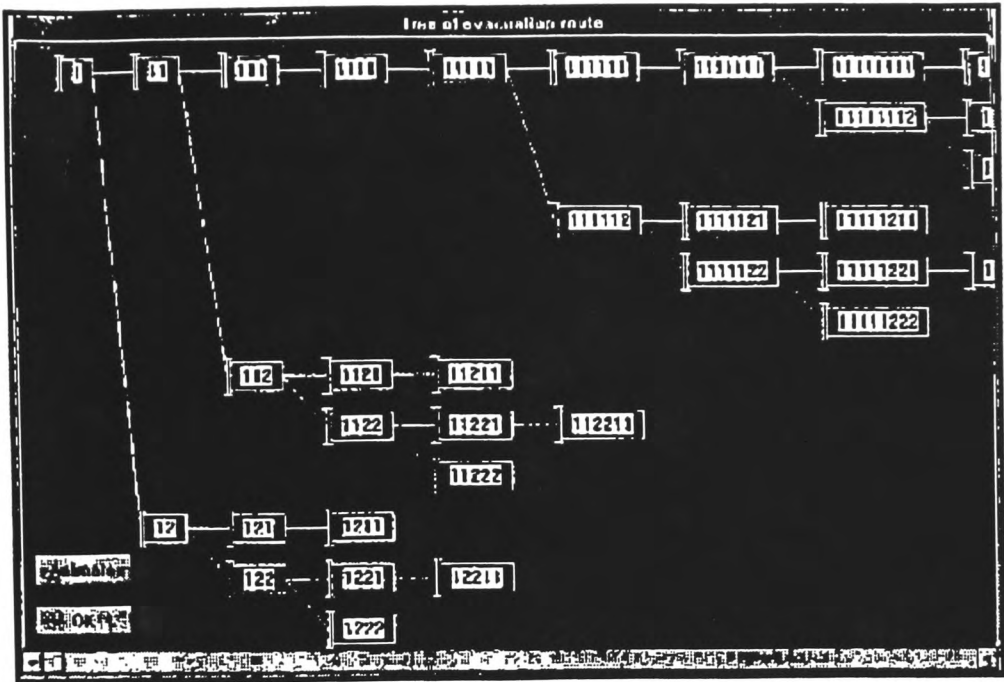


FIGURE 3-32: SCREEN FROM WAYOUT ILLUSTRATING THE TWIG SYSTEM.[48]

Although there is a graphical interface (see Figure 3-32), WAYOUT does not provide the facilities to analyse the data generated within the package, but instead, the data is written to a file which can then be scrutinised using an external editor.

The program does not model response time, behaviour of any type, or physical or psychological reaction to the environment. There seems to be a logical contradiction, in that the developers highlight the effects of behaviour on the speed of movement, and the way in which it decreases the need for minimum evacuation times, but then go on to ignore behaviour completely.

The developers provide some validation results (see Table 3-10) using the data produced from a fire drill for the seven storey Milburn House structure.

TABLE 3-10: VALIDATION RESULTS PROVIDED BY SHESTOPAL AND GRUBITS[48]			
	Number of Evacuees	Time of Evacuation	
		Tested	Computed
Exit 10	248	4'26"	4'03"
Exit 4	40	1'00"	0'40"-1'39"
Exit 8	48	2'36"	2'44"

Data from the flow rates of 3 exits was provided, with other exit data excluded due to the low number of evacuees using those exits. The distribution of times provided for exit 4, were included, as a number of population configurations were examined, which the developers saw as significant. The difference in the results ranged from 9% to 33%. The records from which this comparison is made are incomplete, with only 60% of the occupants involved in the drill being accounted for. It is also impossible to determine the



identity, and exact arrival times of occupants, at specific exits and stairwells These factors, and the existence of discrepancies within the data set, makes the validation process and therefore the results questionable.

This test of the model, is augmented by Horasan and Johnson [190] ,who examined both WAYOUT, and EVACNET+[30,31]. Both EVACNET+[30,31] and WAYOUT established the travel time of ‘normal’ occupants, and both were incapable of coping with any deviation from this standard figure, which might be due a disability or a delaying behaviour. Two scenarios were tested; one involving a primary school, of able-bodied children, and another involving a school whose occupants had special needs. In both scenarios behaviour was seen as a significant effect, as the developers pointed out,

*“Factors such as mobility and dependency, perception of risk, communication, number of supervising staff, and aggressive behaviour, were identified as effecting the detection, definition, and coping behaviour of clients.”[48]*

It was the belief of the developers that the programs modelled evacuations on the basis of ‘normal’ healthy occupants and did not cater for the evacuation of the physically /intellectually disabled, and they determined to prove this by examining two schools, and a centre for disabled. Table 3-11 shows these results.

TABLE 3-11: COMPARISON OF FIRE DRILL RESULTS WITH COMPUTATIONAL RESULTS.[190]

Test Case:	Experimental Results(secs)	EvacNet+ Prediction (secs)	WAYOUT Prediction(secs)
School A (212 students)	260	240	-
School B(365 students)	300	270	-
Centre B (30 clients)	260	-	30

As can be seen, there is an underestimation of the evacuation time of able-bodied pupils from the two schools (with a maximum of a 10% difference of the actual time), as modelled by EVACNET+[30,31]. This might be due to the lack of behavioural considerations. However, once a more severe behavioural effect was introduced (which was evident in Centre B), the discrepancy between model predictions and observation increases.

As EVACNET+[30,31] was used to simulate the school evacuations and WAYOUT was used in the care facility, it is not possible to compare the two models using this data set. The data highlights the difficulties that WAYOUT (with an 88% discrepancy) has with simulating the behaviour of the occupants of the care facility. As such, it is useful in identifying the weakness inherent in evacuation models that ignore behaviour.



In a similar manner to EVACNET+[30,31], the inability of WAYOUT to cater for occupant behaviour, together with its simplistic movement calculations, suggests that it may be of more use in comparing the relative evacuation capability of buildings rather than making statements of absolute evacuation performance.

**B)INDIVIDUAL PERSPECTIVE{ C[15,16] }**

**B)I)RULE BASED{ C [15,16] }**

**CRISP / CRISPII [15,16]**

**CRISP** [15, 16] is a rule-based system developed by the UK Fire Research Station, for the NEXT platform. The NEXT environment is not compatible with other more conventional computer environments including DOS or Windows-based systems. The CRISP software is therefore not easily portable to more conventional computer systems.

CRISP uses probability biased event trees to determine the evacuation behaviour of families in domestic residencies. It utilises a zone fire model to account for the spread of fire products. As in EXODUS [5-7,21-27], the fire products have a physiological effect (expressed in terms of a Fractional Effective Dose), and psychological effects, which influence the decision-making process. The specialised nature of the CRISP model, in that it can only model domestic events, severely limits the usefulness of the model.

CRISP was originally designed as a risk assessment tool for a domestic environment, and as such, is not expected to handle large numbers of people. Social interaction was neglected, but this might be explained by the fact that, it was designed for one type of occupancy, namely domestic, and therefore it might not be expected to cater for the complex social interaction observed in larger structures. In this way collective activity would be less influential, as the domestic setting assumed a local affiliation.

The event-tree probabilities used in CRISP are determined through use of the DELPHI technique, and the whole scenario is then examined using a Monte Carlo approach. This involves repeating the simulation a number of times, subtly changing components, to account for different scenarios. A useful tool featured, is the ability to store the 'seed' used in the random number generator, so that important simulations can be repeated. The technique is dependent upon events being continually checked stochastically, to see if they have occurred and whether this might trigger other events, although,

*"The number of interactions between components may be large, so many conditional probabilities have to be calculated." [15]*

Although it would appear from these techniques that the model is based on probabilistic tenets, the route choice of an individual is purely deterministic, undermining the usefulness of the model itself, so that although many events might occur, once placed in a specific location, an occupant will decide upon the same exit route.

Newer versions allow for the user to edit behaviour, to match their requirements, and to make behaviour specific to their surroundings. This approach side-steps the responsibility of the developer to provide a comprehensive behavioural model, shifting the responsibility onto the user. Prior to the editing facility being included, the level of user input, was considerable. This has now increased with the new feature. This input includes:

- the noise required to wake an occupant
- family type
- the geometry
- material properties
- the probability distributions for stochastic variables, and many more.

CRISP defines internal structures in terms of objects, (which might be a room, a human, a piece of furniture etc.) which interact according to pre-defined rules. The structural objects form a coarse network, around which the individuals move. No information is provided, concerning the movement model used (walking speeds, etc.), other than the decision-making process.

The use of a coarse network might not be as influential as if the model had to cope with large-scale evacuations. However, its use still places restrictions upon the ability to locate individuals inside coarse nodes, and therefore to accurately identify behavioural activities, other than at specified locations.

Human activity is divided into sensory perceptions derived from these objects (which includes smoke, heat, noise) and behaviours, which are initiated by these perceptions. These behaviours are based on the following principle that,

*"[the developers] are not interested in the actual procedure of searching the building, merely in moving the people in a manner that resembles a search, and causes them to take up the appropriate toxic doses." [15]*

This indicates that the physiological results of the activities are seen as more important than the motivation behind the activities and their effect on the surrounding population. The decision process is deterministic, and is taken from a list of behaviours appropriate to domestic dwellings including

- sleep,
- escape,
- fight fire,
- leave,
- rescue,
- wait
- and warn other.

Degrees of difficulty are assigned to escape routes, which the individual is determined to minimise in order to escape, such that occupants will choose the least difficult route. It also accords an individual a complete information set, allowing access to information he/she might not have been privy to. This was necessary in order to alleviate computational problems. This involved the individual being provided with a mental map of the structure, from which to choose their exit route.

Recently the model has been updated to the CRISPII [15,16] model. This has been enhanced so that it can be used under windows-based systems [191].

It now utilises a 2-layer zone fire model to account for the spread of fire products, allowing it to determine the tenability of individual rooms (denoted as  $\xi$ ). This is calculated as the weighted sum of the tenability of the two layers (hot,  $\xi_{hot}$  and cold layers,  $\xi_{cold}$ ) such that

$$\xi = (1-w)\xi_{hot} + w\xi_{cold} \quad (41)$$

The weighting value,  $w$ , is calculated according to the height of the smoke/air interface in relation 1.8m above the floor, such that

$$w = \frac{1 + \tanh\left(\frac{H_{int} - 1.8}{0.05}\right)}{2} [191] \quad (42)$$

The occupant decision-making system in CRISPII is dependent upon the role attributed to the occupant [191]. The occupant is able to perform a number of actions, the nature of which are dependent upon the occupant's role. This information is stored in behaviour tables, where data was derived directly from actual fires [191].

The occupant's initial movement speed is determined by their role within the evacuation and the population density around them. The user is required to determine distribution of speeds available at two different density levels. The occupant's speed will then fluctuate accordingly. The occupant's speed also halves once there are deemed to be travelling on stairwells.

Route planning has been developed so that it is calculated according to a search algorithm that analyses the potential routes that may be adopted by the occupant, according to the coarse nodal mesh. Although long-winded, this process enables long-term routes to be devised according to the tenability and availability of individual rooms, rather than the manual method utilised in the original CRISP model. Movement within rooms is dependent upon pixels. These are non-uniform sub-components that may hold variable numbers of occupants. The adoption of these compartments is dependent upon the occupation levels. Compartments that are 'fully occupied' are ignored by evacuees. This allows more accurate modelling of local navigation than earlier versions of CRISP, which was entirely dependent upon nodes based upon architectural features. These pixels form a contour map designed to make movement towards pixels closer to the desired goal more attractive according to

$$\underline{v}(x, y) = -\underline{\nabla}D(x, y)$$

However, the definition of the enclosure layout is dependent upon the user's ability to enter the room co-ordinates in file format.

A queuing algorithm has been included to assist in the production of accurate flow rates. This allocates evacuating occupants with exit permissions to determine the priority of their evacuation [191].

The interface has been recently expanded to include a virtual reality interface (see Figure 3-33). It is not clear whether this technology is post-processor or involves calculations that impact upon the results.

Both versions of the model require a degree of expertise, on behalf of the user, in both the input and interpretation of data. As mentioned earlier, CRISP/CRISPII requires copious amounts of information, some of which might be considered as specialist knowledge (such as material properties). Furthermore, once results are retrieved, the user

has to be able to sift through vast amounts of information, and then extract the important aspects.

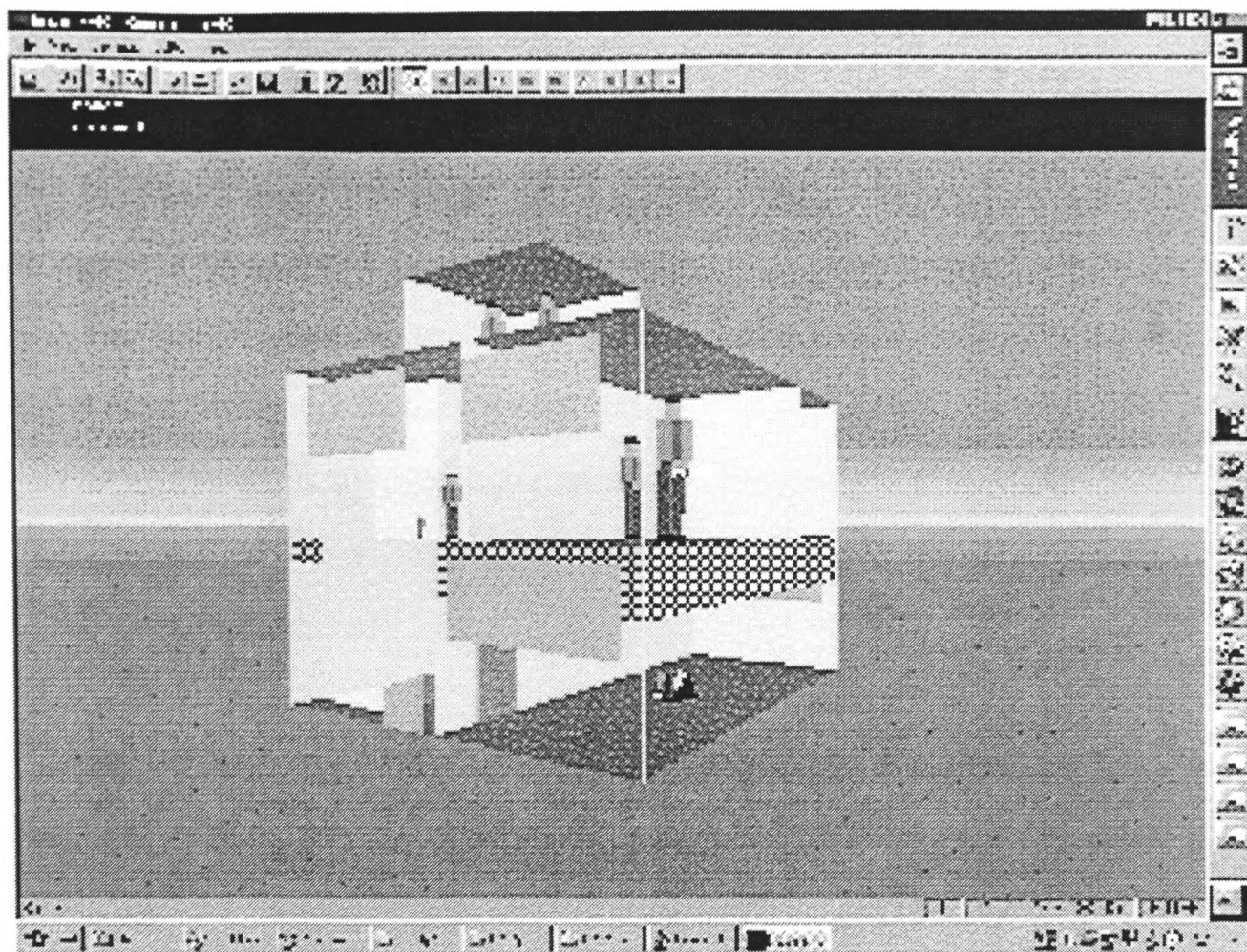


FIGURE 3-33: VIRTUAL REALITY INTERFACE OF THE CRISP MODEL.

No technical information was provided concerning validation for this model, or the expected runtimes. However, during some simulation runs, 3000 runs were required to establish the results. If individual run-times were small this might not pose a problem.

### 3.4 CONCLUSION

Since the first computer-based evacuation model appeared some 17 years ago, great advances have been made both in our understanding of the human response to emergency evacuation situations and in our attempts to model this response. This chapter has been an attempt at compiling and examining the available evacuation models. As such, the chapter contains a discussion of some 20 models. Any omissions that may have occurred are due to the difficulty in obtaining relevant information or through the appearance of information too late to be included in this chapter.

*It has become apparent during this examination, that there is a trend (although far from linear) towards models that include greater behavioural detail. The impact of these developments is strongly dependent upon the methods employed by the models to represent both the enclosure, and the population.*

The success of those models employing extensive behavioural features is tempered by the use of a coarse network, or through the representation of the population as a homogenous group. Both approaches make the description of the effect of events on members of the population far more vague, and more difficult to analyse. Those models that currently appear most promising in accurately describing evacuation behaviour, employ a fine node network, and are capable of identifying individual members of the population (e.g. buildingEXODUS[5-7,21-27], EGRESS [18-20], Simulex [42-44], etc.). By doing so, they are able to produce sophisticated behaviours, and are then capable of distinguishing where these behavioural events take place, and which members of the population are involved.

In terms of software usability, the development of graphical interfaces has vastly improved the ability of the user to fully understand the activities of the model population, as well as simplifying the process of developing evacuation scenarios. The ability to view the simulation reveals qualitative features of the evacuation which otherwise would be lost. Furthermore, it may be possible to generate ‘correct’ evacuation times while not ‘correctly’ predicting the behaviour of the occupants. A graphical run-time interface or post-processor visualiser allows these features to be examined more closely. In addition, the specification and design of the evacuation scenario will be greatly assisted through a well-designed graphical interface. The importance of the ability to visually interpret the simulation is therefore evident. However, it is important not to rely upon visual techniques at the expense of modelling development; this would be counterproductive. Also, irrespective of the level of sophistication of the graphical user interface, the evacuation model is only a tool to be used to aid the engineer in exploring the dynamics of the evacuation scenario. It does not replace good engineering practice.

The overall usefulness of the evacuation model to design engineers is also dependent on the computational cost of performing the simulations. As each scenario is typically run several times and many scenarios may be considered, the simulation speed limits the number of cases that can effectively be performed. Often information concerning typical model run-times is not provided. If this is an oversight, it is unfortunate as this is an important consideration for a potential user.

A number of evacuation models omit a comprehensive description of occupant behaviour or limit the model to a small number of people. The justification used by several developers concern the limitations of computer technology. However, with the increase of processor power and the memory capacity of modern PC computing, models are now available that can simulate large populations, and include complex behavioural attributes that begin to address the complex interactions of structure, environment, human behaviour and procedures. Another fundamental problem with a number of models, related to this, is the inconsistency with which they treat areas of the evacuation process. A number of the models give a disproportionate amount of weight to one particular area of the evacuation process, to the detriment of others. For models to be effective, it is important that they are consistent in their treatment of evacuation factors, and utilise the available technology to its greatest effect.

*The single most important feature that all of the models examined lack is a convincing battery of validation comparisons.* For the most part this is due to a general lack of data suitable for validation purposes. To a certain extent this problem is shared with another branch of fire safety engineering - that of fire modelling.

The problems associated with developing an evacuation database suitable for validation purposes are many. Evacuation performance is dependent on many parameters including: the

- Physical nature of the enclosure (size, number of rooms, number of floors, number of exits size of exits, presence of obstacles, presence of stairs, etc.),
- Function of the enclosure (offices, hospital, prison, school, theatre, etc.),
- Nature of the population (number of people, age/gender distribution, inter-relationships, physical attribute distribution, familiarity with structure, roles, etc.),
- Nature of the environment (night/day, seasonal, debris, signage, smoke, heat, toxic gases, irritant gases, etc.).

The variability of human behaviour compounds these problems making the repeatability of experiments an issue. It is thus vital that an understanding be developed of the role different forms of validation (e.g. qualitative, quantitative, functional) have to play in the general acceptability of these models.



For the purposes of this dissertation, namely to develop a better understanding of occupant evacuation behaviour and to model this behaviour within evacuation models, the buildingEXODUS model has been selected as a means by which this activity might be achieved. This is largely because of its relative sophistication, wide-use and availability. As well as this, its modular design enables further developments to be more easily implemented into the original model. Before further development of the behavioural model could be pursued, a rigorous testing/validation process was undertaken in order to highlight the models capabilities. To this end, several validation cases are presented in Chapter 4 to bolster the existing cases. These cases have been selected from the limited available data-sets as being the most suitable for comparison.



## CHAPTER 4 THE VALIDATION OF THE BUILDINGEXODUS EVACUATION MODEL

Validation is an essential step in the continual development and acceptance of evacuation modelling. While no degree of successful validation will prove an evacuation model correct, confidence in the technique is established the more frequently it is shown to be successful in as wide a range of applications as possible [7]. For the purposes of this dissertation it is vital to gain a detailed understanding of the capabilities of the buildingEXODUS model, given that it has been selected as a framework within which the proposed behavioural developments will occur. This will enable a more coherent behavioural development, where the model capabilities are not duplicated or redundant and will also provide a benchmark against which the developments can be compared.

While the term “validation” is commonly used, its meaning is often misinterpreted. Here validation will be taken to mean the systematic comparison of model predictions with *reliable* information. The information used for validation purposes may comprise experimental data, numerical data, or experiential insight or a combination of these sources. Depending on the nature of the data, the validation may comprise, (i) *component testing* –that establishes whether main model components perform their intended tasks, (ii) *functional validation* – that involves checking that the model possesses the ability to exhibit the range of capabilities required to perform the desired simulations, (iii) *qualitative verification* – that involves comparing the nature of predicted human behaviour with informed expectations. This is important as it demonstrates that the behaviour capabilities built into the model are capable of producing realistic behaviour and (iv) *quantitative verification* – that involves the detailed comparison of model predictions with reliable data generated through an evacuation demonstration [7].

At least two types of qualitative validation may be performed. The first involves the use of historic data. In this case the modeller has full knowledge of the experimental results. The second type involves using the model to perform predictive simulations prior to having sight of the experimental results; a so-called “blind” prediction.

In Chapter 3 some 20 evacuation models were identified and reviewed. One of the features common to all the models identified was a lack of convincing validation data. This provides difficulties in assessing the models and their respective capabilities. As the number and variety of evacuation models increase it becomes essential to provide a

discriminating basis of comparison. Success at a wide range of standard 'validation' exercises provides one means to this end. Furthermore, the move towards performance based building codes and the resulting increase in the use of computer models in demonstrating compliance has accelerated the need to perform convincing validation of all fire safety models. While no degree of successful validation will prove an evacuation model correct, confidence in the technique is established the more frequently it is shown to be successful in as wide a range of conditions as possible.

However, to date, little effort has been invested in the systematic comparison of various evacuation models with common experimental data. This is primarily due to the lack of suitable data for the validation of evacuation models. Similarly, the majority of evacuation trials are not conducted for model validation purposes but to demonstrate the suitability of building design/staff procedures or to gauge compliance to a regulation or standard.

As a result, modellers are forced to rely on secondary data from actual evacuations, data usually concerning non-emergency movement, staged trials or procedural tests. In most cases insufficient data is recorded to allow a detailed 'validation' of evacuation models. All of these data sources pose problems that limit their suitability as validation data sets.

There are many difficulties associated with developing a data set suitable for the validation of evacuation models. These problems are dependent upon a number of parameters including:

- the nature and function of the enclosure in which the evacuation is conducted,
- the nature of the population involved in the evacuation and their information levels,
- and the nature of the environment in which the evacuation is conducted.

In addition, the experimental data set should be as complete as possible, with all aspects of the geometry, population and procedures recorded. This allows the modellers to concentrate upon validating the model at hand, instead of defining, investigating and justifying assumptions and the resulting dubious predictions. If this information is collected, fewer assumptions and estimations need to be made by the modellers performing the validation and hence the more reliable the validation.

These difficulties are exacerbated by the variability of uncontrolled human behaviour during the evacuation. Thus questions concerning repeatability of the experimental data arise. Ideally, when collecting data for model validation purposes, the trial should be repeated several times in order to determine the range of likely performances thereby

minimising the influences of unusual or atypical behaviour. Hence, for model validation purposes, for a given building configuration, specified type of occupancy and specific type of scenario, it is necessary to determine the *range* of evacuation performance likely to be achieved. This requires repeating the evacuation a number of times. Unfortunately, when dealing with evacuation analysis in the built environment, the existence of such data sets is not guaranteed.

Finally, computer models are continually being adapted and improved by their developers. As a model develops to include more sophisticated techniques, so the accuracy and usefulness of these techniques should be examined in isolation, and in conjunction with the rest of the model. This is necessary so that the sensitivity of the model to new factors does not destabilise the previous capabilities of the model. Software validation should thus be considered an on-going activity. Validation is not a 'once and forget task', but should be considered as an integral part of the life cycle of the software.

In this chapter several validation cases of the buildingEXODUS [5-7,21-27] evacuation model will be attempted through comparison with the Stapelfeldt experiments [192] the evacuation carried out at Milburn House [193] and the Tsukuba evacuation exercise [194]. For further details the reader is referred to the original reports [25,27]. These data sets have previously been used to validate other evacuation models [34,35,48,195]. This will then demonstrate the ability of the model to cope with a variety of different scenarios as well as highlighting the behavioural shortfalls of the model. This will then allow any deficiencies in the existing capabilities of the behavioural model to be determined and may also suggest potential remedies to these problems. It will also provide information concerning potential problems in the development of the advanced behavioural features suggested in this dissertation, allowing these problems to be addressed prior to their detailed analysis.

#### 4.1 VALIDATION 1: THE STAPELFELDT EVACUATION

The Stapelfeldt [192] experiments were conducted in 1986 and involved the evacuation of one hundred police cadets from a small room within a school gymnasium. These evacuations were carried out specifically to generate information concerning evacuation movement. Due to the relative completeness of the data-set, and the simplicity of the geometry, the experimental results are of particular use in *quantitative* validation.

#### 4.11 THE EXPERIMENT

One hundred police cadets were grouped in a school gymnasium producing a reported population density of 4 persons/m<sup>2</sup> around the exit. The experimental evacuations were conducted through a single exit of variable width, utilising exit widths of 0.75m, 0.80m, 1.50m and 1.60m. The methods used to implement these changes in exit width were not given, but from graphical evidence [192], it appeared to be achieved by the opening/closing of a set of double doors.

The gender distribution amongst the occupant population is unknown, although there is an indication that the population is made up of young, fit adults [192,195].

The data generated from this experiment suffers from the fact that each experiment was conducted only once, i.e. there was no replication of the experiments. Thus the evacuation times provided for each exit width represents the result from a single experiment rather than an average produced from a number of repeat trials. Had each trial been repeated several times, a range of evacuation times would have been generated with an upper and lower bounds and a standard deviation.

The experimental data reported here concerns the evacuation of the room under normal conditions, without simulated 'panic'/increased motivation to evacuate and without the influence of fire hazards such as smoke or heat. Evacuations involving an increased motivation were reported, however these are not considered appropriate for inclusion here due to the general ambiguity concerning the conditions of the evacuation.

The dimensions of the compartment do not appear to be explicitly mentioned in the text [192,195]. However, from a diagram in the original German text [192], it appears that the room was rectangular, with a width of 2.9m. While the length of the compartment is not provided, this is not significant so long as it was long enough to maintain a density of 4 persons/m<sup>2</sup> around the exit with a population of 100 cadets. Furthermore, the times provided by the experimental data only concern the total evacuation times, and not the time of the first occupant to exit. It is assumed that due to the close proximity of the occupants to the exit and the experimental control exerted, those closest to the exit pass through almost instantly.

4.12 EXPERIMENTAL RESULTS.

The data generated from this experiment is presented and compared against predictions based on the equations of Predtechenskii and Milinskii [150], and the Effective Width Model [56,177] (see Table 4-1) as reported in [195].

The evacuation equations generated by Predtechenskii and Milinskii [150] are based upon non-emergency occupant movement within a train terminal (see Chapter 2). These equations relate occupant flow and velocity with the overall population density.

The Effective Width Model [56,177], produced by Pauls, imposes similar assumptions to those in the Predtechenskii and Milinskii model, whilst also concentrating upon the importance of the occupant’s usage of the enclosure (see Chapter 2).

TABLE 4-1: EXPERIMENTAL DATA COMPARED WITH PREDICTIONS BASED ON PREDTECHENSKII AND MILINSKII [150], AND THE EFFECTIVE WIDTH MODEL [56,177]. NUMERICAL PREDICTIONS TAKEN FROM PAULSEN ET AL [195].

Exit width (m)	Experimental results (s)	Predtechenskii And Milinskii (s)	Effective Width Model (s)
0.75	55	69 - 74	168
0.80	50	65 - 69	152
1.50	30	35 - 37	63
1.60	26	32 - 35	58

As can be seen in Table 4-1, the Predtechenskii and Milinskii equations produce significantly longer evacuation times than those observed in the experiment. The mean evacuation times produced by these equations over estimate the experimental results by an average of 28%, with the 1.6m exit producing the best agreement (within 20%) and the 0.8m exit producing the worst agreement (within 34%).

The results generated using the effective width model are even more inaccurate, with an average over-estimation of 161%, with the 1.5m exit producing the best agreement (within 110%) and the 0.8m exit producing the worst agreement (within 204%). The over estimations of Predtechenskii and Milinskii and the effective width models highlight the conservative nature of these types of equations in evaluating overall evacuation times.

4.13 SPECIFYING THE BUILDINGEXODUS SIMULATIONS.

In this section the problem set-up and specification used for the buildingEXODUS simulations are described. Before buildingEXODUS can be used to run the various

simulations it is necessary to specify the precise nature of the geometry and the population. As there are several ways in which this can be done it is essential to clearly specify the geometry and population. This will in turn define the nature of the scenarios simulated.

#### 4.13.1 SPECIFYING THE POPULATION.

The Stapelfeldt data used in this study was generated under “normal” or “non-panic” conditions [192,195]. Thus, the buildingEXODUS simulations used the NORMAL behaviour option and hence it was not necessary to set the PATIENCE attribute for the occupants.

The population were assigned ages of between 20-30 years, and were all deemed to be male. This assumption is based upon the claim made by Paulsen et al [195] that the population was uniform. In buildingEXODUS, with the exception of prescribing travel speeds on stairs, the gender and age attributes are descriptive in nature and are used as a guide to setting other personal attributes. Hence the simulations presented here will not be sensitive to the age and gender distributions. Without any additional information, the maximum *travel speed* distribution for the population assumes the default setting of 1.2 - 1.5 m/s.

Another population attribute, which can be set in buildingEXODUS, is the *RESPONSE TIME* for each individual. This is the time elapsed between the start of the evacuation and the time the individual begins to actively evacuate i.e. move towards an exit. Due to the controlled nature of the event (i.e. there was no sociological or psychological impediment to the occupants not moving off instantly), the response time was set to 0 seconds for all occupants during these simulations. This assumption would normally be considered unjustified in more realistic scenarios and a response time distribution would be imposed on the population. Here it is assumed that the nature of the experiment encouraged a uniform prompt response from the population involved.

Within buildingEXODUS conflicts are resolved partially through the occupant attribute *DRIVE*. If the population is given a uniform drive, its members are considered to be equally motivated and highly competitive. Each conflict would be contested by equally matched individuals, who were not prepared to let the other pass. Within buildingEXODUS this would result in long delays, as each conflict would need to be randomly resolved. If the population is made up of people with differences in their

drives, conflicts will be resolved more quickly and incur less delays, resulting in a smoother evacuation.

As the experiments were undertaken under non-competitive conditions, a uniform drive distribution within the simulated population is not considered appropriate. Under normal conditions where a diverse population can be expected, the default setting for the drive distribution would be used. This results in a drive distribution of some 67%. This effectively results in the normalised difference between the population maximum and minimum drives being 67%. As the population used in the experiment is made up of police cadets they may be considered to be more uniform in their abilities than a typical cross section of the public. This would suggest that the default distribution might be too wide. It was therefore decided to model the population using a 40% distribution in the drive attribute.

To demonstrate the impact of drive, five other drive distributions was also used namely a 10%, 20%, 30%, 50% and default spread.

#### **4.13.2 SPECIFYING THE GEOMETRY.**

Using a mesh spacing of 0.5m, the geometry is specified as 3m in width and 8.5m in length thus enabling the required population density of 4 persons/m<sup>2</sup> to be maintained. In this report, two exit widths are examined: the 0.8m and the 1.5m exit openings.

An important parameter used to describe the flow capabilities of an exit is the exit flow rate. buildingEXODUS allows several methods to specify the flow rate through an external exit. The first method allows the software to determine the flow rate as a natural consequence of the width of the exit and the behaviour of the individuals passing through the exit, this is referred to as “free flow”. However, in certain situations - such as when attempting to satisfy national prescriptive regulations - it is necessary to cap the flow capability of an exit by an agreed amount. This is achieved by allowing the flow rate to be capped using either a user-specified value or a pre-defined rate so that the flow rate will not exceed this value. Table 4-2 lists the pre-defined exit flow rates in buildingEXODUS.

This assumes that a linear relationship exists between exit width and the flow rate. According to the literature, this assumption is only valid for exits with a width in excess of 1m [23 - 26]. These options are thus only used in the case involving the 1.5m exit.

TABLE 4-2: EXIT UNIT FLOW RATES AVAILABLE WITHIN BUILDINGEXODUS

Name	Unit Flow Rates (occ/sec/m)
HMSO[185]	1.33
Hankin[156]	1.46
Fruin[66]	1.33 - 2.00
Polus[154]	1.25 - 1.58
User Def	0 - $\infty$

4.13.3 THE SCENARIOS.

Two different cases were run with the population and geometry described in sections 4.13.1 and 4.13.2: one involving the 1.5m exit and one involving the 0.8m exit. For the 1.5m exit case, five scenarios were run involving the use of the HMSO[185], Hankin[156], Fruin[66], Polus[154] and free flow exit conditions.

Each scenario was repeated five times producing a mean and range of evacuation times. Each repeat was an exact repeat i.e. the population and geometry attributes were not altered in any way, including the start locations of the people. Of all the variations performed for testing purposes, the cases involving the 40% drive distribution with free flow exit flow rate specification is the recommended set-up conditions for this case.

4.14 THE BUILDINGEXODUS PREDICTIONS OF THE STAPELFELDT EXPERIMENTS.

All the simulations presented in this section were carried out using a Pentium 133 MHz PC with 16 MB of RAM. These simulations were completed in between 30 to 60 seconds depending on the nature of the simulation

4.14.1 BUILDINGEXODUS PREDICTIONS FOR THE 1.5M EXIT.

In total, some 150 simulations were run for the 1.5m exit case. The recommended problem specification for this case involved the 40% drive distribution with the free-flow exit flow rate specification. The measured evacuation time for this case was 30.0 seconds (see Table 4-1). The buildingEXODUS simulation generated results for the various prescribed flow cases are summarised in Table 4-3.

From examining Table 4-3 it is clear that the prescribed flow rates significantly over predict the evacuation times by between 56% (Fruin with default drive distribution) and 103% (HMSO with 10% drive distribution). Of all the prescribed flow rates, the HMSO flow rates consistently produce the poorest agreement with experimental results and are



the most conservative. It is also interesting to note that the results produced by buildingEXODUS with the prescribed flow rates are consistent with those generated by the Effective Width Model [56,177] (see Table 4-1).

TABLE 4-3: COMPARISON OF THE BUILDINGEXODUS GENERATED MEAN EVACUATION TIMES FOR THE 1.5M EXIT CASE. RESULTS IN PARENTHESIS INDICATE THE DISTRIBUTION PRODUCED BY THE REPETITION OF THE SIMULATION.

Drive Distribution (%)	HMSO (sec)	Hankin (sec)	Fruin (sec)	Polus (sec)	Free Flow (sec)
10	61.0 [60.6-61.9]	56.7 [54.6-58.1]	53.9 [53.4-54.7]	59.4 [59.0-59.9]	34.1 [31.4-35.2]
20	58.8 [58.4-59.6]	55.7 [55.2-56.5]	52.8 [51.9-54.2]	57.9 [56.3-59.5]	33.2 [27.8-34.9]
30	59.0 [58.4-59.6]	55.7 [54.9-56.3]	52.3 [51.4-53.6]	56.6 [55.0-59.1]	30.3 [27.9-34.4]
40	58.5 [57.6-60.0]	54.3 [52.8-55.5]	50.9 [48.9-52.0]	55.9 [55.1-57.3]	30.3 [28.8-32.3]
50	58.1 [57.1-59.3]	53.1 [50.1-55.6]	50.8 [49.5-52.6]	56.1 [54.4-58.1]	30.0 [28.8-31.4]
default	55.5 [55.2-55.8]	51.4 [50.6-52.1]	46.8 [45.9-48.2]	54.3 [53.9-54.7]	29.0 [26.4-31.6]

In contrast, the free flow results produce the best agreement with experimental results. These vary from under predicting the evacuation time by 1.0 seconds (i.e. 3.3% for the default drive distribution) to over predicting the evacuation time by 4.1 seconds (i.e. 13.6% for the 10% drive distribution). In the situation investigated, the free flow condition produces significantly larger flow rates than those imposed by the prescribed conditions. The instantaneous unit flow rates predicted by buildingEXODUS over 5 second intervals are depicted in Figure 4-1. Based on the mean evacuation times, under free flow conditions, buildingEXODUS achieved unit flow rates of between 1.96 - 2.30 p/m/s. These unit flow rates are in line with those measured in the experiment. Indeed, from the original evacuation experiments the flow rates generated were calculated to be approximately 2.22 p/m/s. These unit flow rates are significantly and consistently higher than any of the achieved predefined flow rates, which varied from 1.09 p/m/s (HMSO, 10% drive distribution) to 1.4 p/m/s (Fruin, default drive distribution).

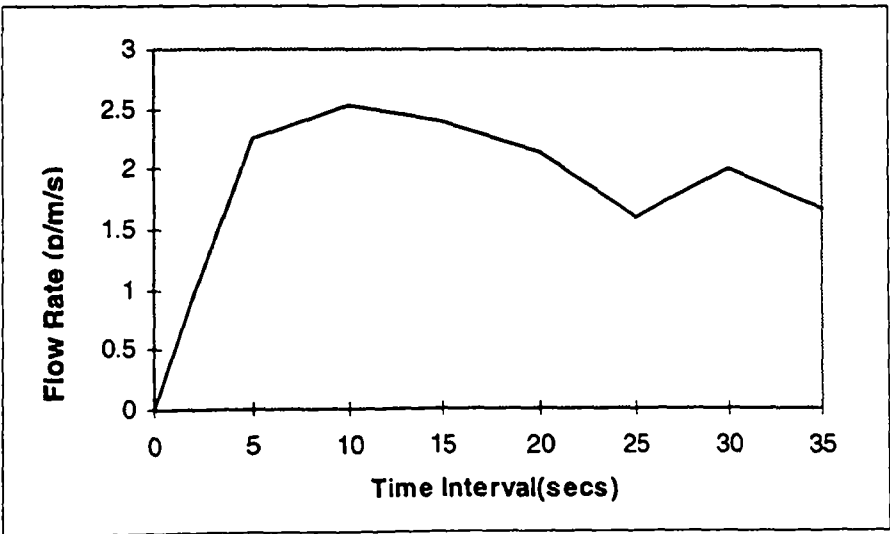


FIGURE 4-1: BUILDINGEXODUS PREDICTED UNIT FLOW RATE DETERMINED IN 5 SECOND INTERVALS FOR THE FREE FLOW CASE WITH 40 % DRIVE DISTRIBUTION.

It is also interesting to note that the results produced by buildingEXODUS under free flow conditions are consistent with those generated by Predtechenskii and Milinskii [150], (see Table 4-1).

As expected, the nature of the drive distribution has a significant effect on the overall evacuation time. As the spread in population drives decreases from the default setting to a distribution of 10%, the evacuation times increases from 55.5 sec to 61.0 sec (i.e. an increase of 9.9%) in the case of the HMSO flow rates and 29.0 sec to 34.0 sec (i.e. 17%) in the free flow conditions.

As described in section 4.13.1, a small range in drives is expected to result in long conflict resolution times and hence longer evacuation times. A wide range in drives results in conflicts being resolved more quickly, resulting in shorter evacuation times. Furthermore, as the situation modelled involved a geometry with only a single exit, a large population and high resulting population densities, many conflicts can be expected and hence the conflict resolution time can be expected to have a significant effect on the total evacuation. Under more typical situations, conflict resolution, while of significant importance to the individuals involved, does not exert such a major influence on the overall evacuation times.

The 40% drive distribution was the recommended setting for these scenarios (see section 4.13.1). Using the various exit flow rate settings this produces mean evacuation times of; 58.5 sec for HMSO (over prediction of 95%), 55.9 sec for Polus (over prediction of 86%), 54.3 sec for Hankin (over prediction of 81%) and 50.9 sec for Fruin (over prediction of 70%). The free flow conditions produced a mean evacuation time of 30.3 sec, resulting in an over prediction of 1%. Thus the free flow conditions with the 40% drive distribution produces very good agreement with the single experimental result. The five repeat cases of the free flow condition produced evacuation times of 28.8, 29.0, 30.3, 31.1, and 32.3 seconds all of which are within 8% of the actual measured evacuation time.

It is worth noting that little difference in mean evacuation times occurs for drive distributions ranging from 30% to the default 67% (see Figure 4-2) under free flow conditions. A difference of only 1.3 seconds or 4.5% results from imposing a drive distribution of 30% to 67%.

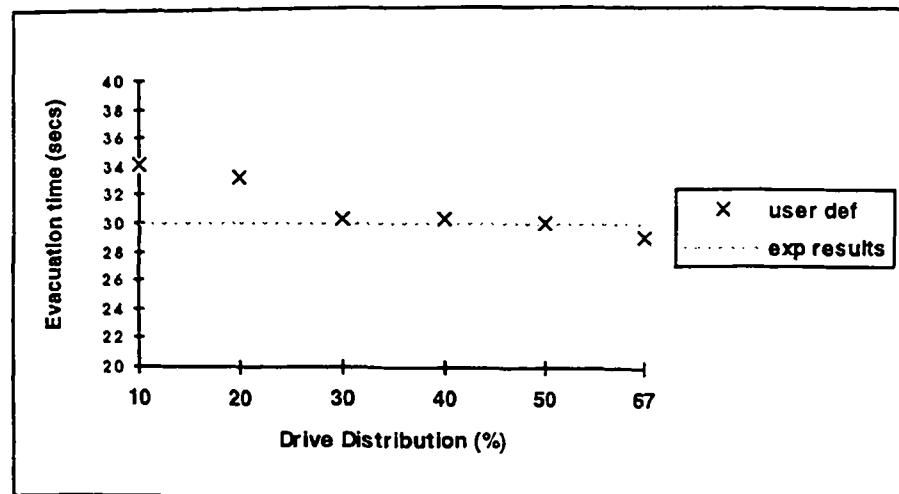


FIGURE 4-2: MEAN EVACUATION TIMES PRODUCED USING THE FREE FLOW CONDITIONS.

As described in section 4.13.1, the drive distribution can be interpreted as representing the occupants' motivation to escape in relation to the rest of the population. Occupants with a high degree of motivation relative to other occupants are attempting to exit by implementing a short-term optimal route; contesting and probably winning all conflicts en route. In contrast, occupants with a low degree of motivation relative to other occupants are less resolute in maintaining an unbroken travel path and give way to other more motivated occupants. It should be remembered that within buildingEXODUS, an occupant's motivation or drive could be assigned on the basis of age, gender etc., or on the perceived seriousness of the situation.

These results (see Table 4-3) support the initial recommended drive distribution. The results seem to imply that the resolution of these conflicts during the actual evacuation are not as punishing (i.e. time consuming) as would be expected if the population were aggressively attempting to evacuate, or if they had truly uniform capabilities.

This suggests that there was a degree of co-operation between the occupants. Occupants choose to resolve conflicts due to the familiarity between them, and not utilise aggressive or assertive evacuation policies. This may be considered similar to typical non-emergency evacuation conditions.

An alternative explanation would be that the population was not uniform in its evacuation capabilities. The implication here being that occupant conflicts are resolved quickly due to considerable differences in the occupant's determination and ability to evacuate. Due to the claims concerning the similarities of the population involved in the experiment [192,195], this is considered unlikely. Furthermore, due to the non-emergency

nature of the evacuation [192,195], the evacuees would be less likely to have taken advantage of any apparent superiority in their physical and psychological attributes.

In order to investigate the sensitivity of the simulations to random variations in occupant start locations and personal attributes a series of 36 additional simulations for the 40% drive distribution were performed. These simulations involved the generation of four different populations. These populations were generated as random variations of the occupant attributes within the upper and lower constraints defined in section 4.13.1. Each simulation for a given population and occupant start location was repeated three times. Furthermore, three different random sets of start locations were used for each of the populations. Thus nine repeat simulations were performed for each population. The results for these simulations are presented in Table 4-4.

The mean evacuation time for the nine simulations for each of the four populations is 30.8, 30.0, 30.6, and 29.9 seconds producing a variation of 3%. The mean evacuation time for the 36 simulations is 30.3 seconds with a range of 26.4 to 33.6 seconds. This compares with a mean evacuation time previously determined of 30.3 seconds with a range of 28.8 to 32.3 seconds. The variation produced by random changes in the population attributes and random changes in start locations appears to be similar to the natural variation seen in simply repeating the simulations. Thus in this case the evacuation times are not sensitive to random variations in occupant starting locations or occupant attributes. This is to be expected considering the nature of the scenario i.e. small geometry, high population densities and the similarity in the population.

**TABLE 4-4: BUILDINGEXODUS GENERATED EVACUATION TIMES FOR EACH OF THE FOUR POPULATIONS WITH THREE DIFFERENT RANDOMISED START LOCATIONS AND 40 % DRIVE DISTRIBUTION.**

	Evacuation Time (secs)			
	Pop 1	Pop 2	Pop 3	Pop 4
Random1	28.1	28.9	29.1	26.4
	33.1	28.8	27.6	27.1
	30.8	27.8	27.9	28.1
Mean	30.2	28.5	28.2	27.2
Random2	30.1	27.1	32.1	31.1
	31.4	32.3	30.9	30.9
	27.3	32.9	30.8	28.3
Mean	29.6	30.8	31.3	30.1
Random3	30.9	29.8	33.6	32.6
	33.3	30.9	33.4	32.4
	31.8	31.6	29.8	32.4
Mean	32.0	30.8	32.3	32.5

Finally, while the simulations were set up to represent non-emergency evacuations, an indication of the possible evacuation times achievable under emergency conditions is

possible. Part of the conditions required for the simulation of emergency evacuations involves imposing a narrow drive distribution. The results for the 10% drive distribution for the free flow exit conditions suggest that mean evacuation times may increase from 30.3 sec (40% drive distribution) to 34.1 sec, an increase of 13%.

4.14.2 BUILDINGEXODUS PREDICTIONS FOR THE 0.8M EXIT.

As the exit is less than 1m in width, it is inappropriate to use the prescribed exit flow rates described in section 4.13.2. Hence, for the 0.8m exit only the free flow conditions are examined. As in the previous case, five repeats are performed for each drive distribution. This results in some 30 simulations being run for the 0.8m exit case. The recommended problem specification for this case involved the 40% drive specification. The measured evacuation time for this case was 55.0 seconds (see Table 4-1). The buildingEXODUS generated results for this case are summarised in Table 4-5. For each case, the mean and range of numerical predictions are presented.

TABLE 4-5: COMPARISON OF THE BUILDINGEXODUS GENERATED MEAN EVACUATION TIMES FOR THE 0.8M EXIT CASE. RESULTS IN PARENTHESIS INDICATE THE DISTRIBUTION PRODUCED BY THE REPETITION OF THE SIMULATION.

	buildingEXODUS drive distribution (%)					
Drive Dist.	10	20	30	40	50	default
Mean	66.2s	63.5s	56.7s	55.5s	54.5s	51.5s
Range	[62.3-69.1]	[58.1-69.3]	[54.6-59.6]	[54.6-56.4]	[51.6-58.3]	[50.1-53.1]

Comparing the results generated by the experimental evacuation (see Table 4-1) and the results generated by buildingEXODUS we see quite a good degree of correlation between the two (see Table 4-5).

These vary from under predicting the evacuation time by 4.9 seconds (i.e. 8.9% for the default drive distribution) to over predicting the evacuation time by 14.3 seconds (i.e. 26% for the 20% drive distribution). In this scenario the free flow condition produces large unit flow rates however, they are broadly in line with those measured in the experiment. Based on the mean evacuation times, buildingEXODUS achieved unit flow rates of between 2.01 - 2.59 p/m/s. From the original evacuation experiment, the unit flow rate was calculated to be approximately 2.42 p/m/s.

Once again it is interesting to note that the experimental results and those produced by buildingEXODUS are broadly similar to those generated by Predtechenskii and Milinskii [150], while being considerably different from that predicted by the effective width model [56,177](see Table 4-1).

As in the previous case, the drive distribution has a significant effect on the overall evacuation time. As the spread in population drives decreases from the default setting to a distribution of 10%, the mean evacuation times increases from approximately 52 sec to 66 sec (i.e. an increase of 29%). However, in the case of the 1.5m exit the change in mean evacuation times (for the free flow case) amounted to only an 18% increase in evacuation times whereas in the 0.8m exit we see a 29% increase. This difference can be explained by the increased number of conflicts expected for the narrow exit case compared to the wide exit case as occupants are engaged in more interactions as they attempt to exit via the smaller opening.

#### **4.15 THE OTHER STAPELFELDT CASES**

The cases examined in this section correspond to the 0.8m and 1.5m exits. Model predictions for the 0.75m and the 1.6m exit were not presented.

The simulations were produced using the buildingEXODUS default mesh spacing of 0.5m, thus a node is placed every 0.5m. In situations where the physical distance is not exactly divisible by 0.5m, an approximation is necessary. If the fractional spacing is between 0.5m and 0.75m a single node is usually recommended and so the simulated exit is slightly narrower than the actual exit.

If the fractional spacing is between 0.75m and 0.99m, two nodes are usually recommended and so the simulated exit is slightly wider than the actual exit. Whichever approximation is used, it is advisable to perform a sensitivity analysis to gauge the impact of adding/ignoring the node, this is especially advisable for the 0.75m fractional spacing.

Under free flow conditions this is all that can be achieved using the 0.5m default spacing. Thus under these conditions, the 1.5m and 1.6m exits would produce the same predicted evacuation times (i.e. as presented in section 4.14.1) using the recommended three nodes for the exit width. Similarly, the 0.8m and 0.75m exits would produce the same predicted evacuation times (as presented in section 4.14.2) using the recommended two nodes for the exit width.

However, for exits above 1m in width, in addition to free flow conditions it is possible to specify prescribed unit flow rates. In these cases another approach is to modify the

maximum unit flow rate to reflect the actual maximum flow rate (NOTE:  $\text{Flow Rate} = \text{Unit Flow Rate} \times \text{Width}$ ). For example if the actual width of an exit is larger than the simulated exit, the user should compensate by increasing the Unit Flow Rate, and conversely, reduce the Unit Flow Rate if the simulated exit is wider than the actual exit.

#### 4.16 POSSIBLE DEFICIENCIES WITH THE STAPELFELDT DATA SET.

While building EXODUS appears to have produced reasonable agreement with the provided experimental data, it is useful to highlight possible deficiencies in the Stapelfeldt data-set that make it less than ideal for model validation purposes. Fundamentally, these occur in three areas: occupant details, occupant motivation and information concerning the evacuation runs.

The use of specialist populations such as police cadets biases the result of any evacuation experiment. Wherever possible, a population representative of the intended target population should be utilised. While a specialist population was used in these experiments, the gender, age and location of the occupants were not provided. However, the effects of these omissions are limited due to the non-emergency nature of the event, the uniformity of the population and the high density of the population that would cause a significant impediment to occupant movement. Furthermore, the physical and psychological advantages that might have been evident due to the differences in the population are unlikely to have contributed to the evacuation due to the non-emergency nature of the event. In addition, the importance of the starting location of individual occupants is greatly diminished due to the high population density. The exact identity and starting locations of individuals would have had an increased importance had the population been expanded to include older or less mobile occupants.

The manner in which the occupants' movement was instigated would have affected the speed with which they evacuated. However, the fact that the event is non-emergency, where the occupants are expected to move in a more restrained fashion, may have reduced the importance of this factor.

Finally, it is worth noting that learning effects may have influenced the experimental results. It is not clear from the report of the experiment [192] the order in which the evacuations were conducted or if the same people were used for all the experiments. If the same population was used for all the experiments, they may have learnt from their previous experiences thus influencing the outcome of the experiment.

As noted earlier, a significant deficiency with the experimental data concerns the fact that only a single experiment was conducted for each exit width. Had the experiments been repeated several times for each exit configuration a range of experimental results would have been obtained indicating the natural variation that could be expected in these cases.

This issue has been addressed in aviation evacuation research. Over the past six years, the U.K. CAA has sponsored a series of large-scale competitive evacuation trials from a single aisle aircraft using a single exit [142]. These trials were designed to answer specific operational questions concerning passenger behaviour. This work has recently been extended to include competitive evacuations through multiple exits and the role of cabin crew intervention [143]. All these experiments involve using specially recruited volunteers, drawn from the general public and performing multiple repeats of each scenario in an attempt to address the issue of repeatability.

## **4.2 VALIDATION 2: THE MILBURN HOUSE EVACUATION EXPERIMENT**

This comparison is based upon the study of a fire drill conducted at Milburn House, Newcastle-upon-Tyne, on Thursday 28th November 1991 [193,196]. Milburn House consists of eight floors and is a multi-occupied office building, constructed at the turn of the century. The building was used mainly for office activities. The exercise was pre-arranged by the Tyne and Wear fire brigade who carried out timings and retrieved information from participants as part of a fire alarm response and evacuation examination. A total of 381 people took part in the evacuation.

The Milburn House evacuation data has been used several times as a validation data set for various evacuation models [34,35,48]. In this study the Milburn House data set will be examined for its suitability as a quantitative and/or qualitative validation data set and where suitable, used as validation data for the building EXODUS model.

### **4.21 THE GEOMETRY.**

Milburn House (see Figure 4-3 and Figure 4-4) is built into a steep hillside, with street exits occurring on all but the top two floors due to the hillside (see Figure 4-4). According to the report, only seven of the available floors were used during the evacuation. The floors are labelled A to G with G being the ground floor and A being the highest floor. The building is irregularly shaped (see Figure 4-3) and each floor consists



of a number of offices, long corridors, some large open spaces, a bar and restaurant and five staircases. The building measures approximately 90m by 65m.

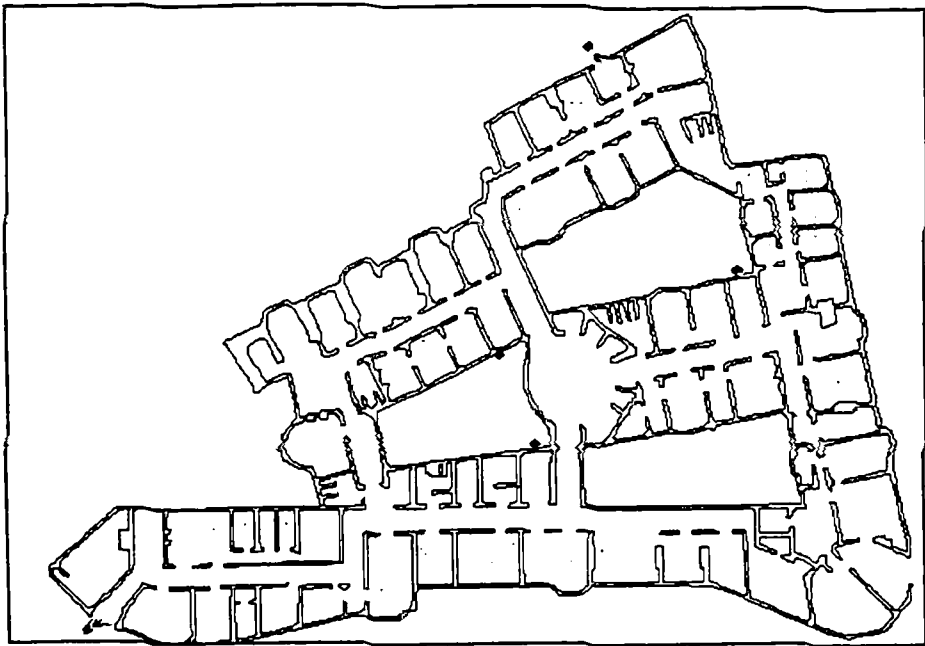


FIGURE 4-3: FLOOR D OF MILBURN HOUSE.

Milburn House possesses five main staircases, labelled orange, blue, brown, green and red stairs, and 10 exits located on various levels (see Figure 4-4). The evacuation assembly area was located external to the building by the fifth floor (floor C).

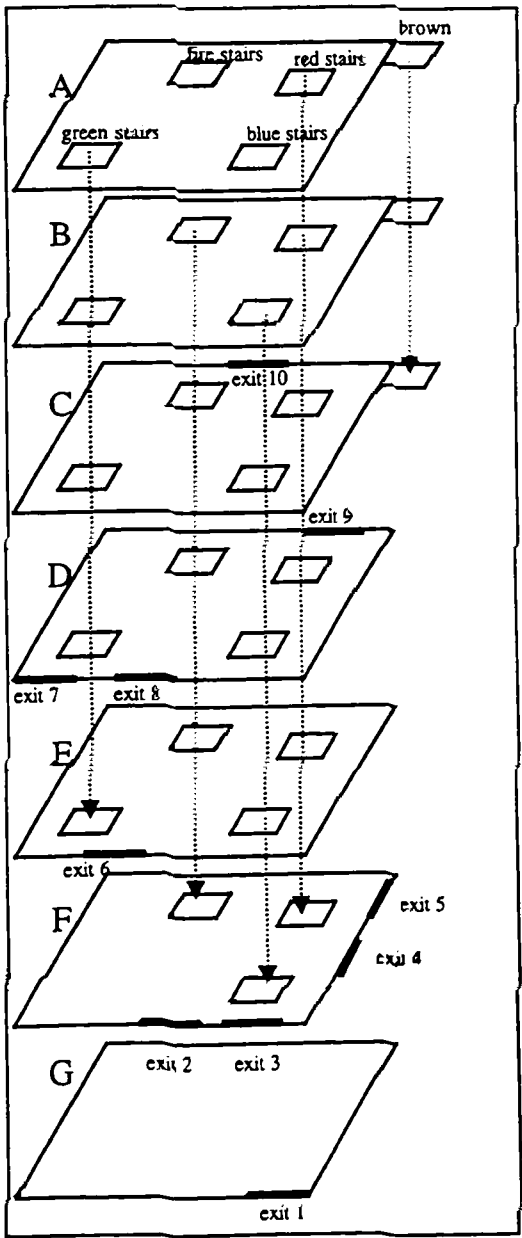


FIGURE 4-4: MILBURN HOUSE SCHEMATIC, IDENTIFYING THE POSITION OF THE EXITS AND STAIRWELLS

## 4.22 THE POPULATION

A total of 381 people took part in the evacuation. The precise distribution of the population between the various floors is not known for certain nor is the exact location of individual occupants within a floor. No break down is available of the age, gender or ability level of the participants.

## 4.23 THE EXPERIMENTAL RESULTS

### 4.23.1 INTRODUCTION

The fire drill was attended by the Tyne and Wear fire brigade who carried out timings and retrieved information from participants. The observers recorded the minimum and maximum time it took occupants to pass them, and the number of occupants that did so, without recording individual times of arrival.

To simulate the occurrence of a fire, one of the staircases was deemed out of bounds. However, a number of occupants still used the fire stair. As the fire drill was prearranged, most of the employees were aware of the drill, and were also aware of the position of the assembly area. The occupant's prior knowledge of the evacuation drill and hence their knowledge of the non-emergency nature of the evacuation may have influenced their response times and their occupant movement rates.

Questionnaires [196] were handed out to all of those that took part. All of those occupants on floors F and G returned the questionnaire, whereas the response rate on floors A-E was 60.8%. This response rate is significant as the behaviour exhibited by those occupants on floors F and G was considered to be of least interest - there was little occupant interaction and occupants chose the nearest exit. No information is available concerning those occupants who did not return the questionnaires.

The questionnaires were designed to retrieve information concerning: the reason for leaving the building, the response times, occupant starting position, the choice of exit/staircase, the exit/staircase usually used, occupant attempted use of 'fire' staircase, whether blockages/delays were experienced on exiting.

The questionnaires contain information from 242 evacuees or 63.5% of participants. As not everyone responded, no information relating to the starting location of certain occupants is available. It is therefore not possible to specify with certainty the room or even the floor on which everyone started from.

4.23.2 STAIR AND EXIT USAGE

The raw data concerning stair and exit usage on a floor by floor basis is presented in Table 4-6 [196]. In addition, the total number of people using each exit was recorded as was the time for the first and last person to use the exit (see Table 4-7).

TABLE 4-6: OCCUPANT MOVEMENT ON EACH LEVEL AS REPORTED IN THE QUESTIONNAIRE RETURNS [196].

LEVEL A	No.Occ	LEVEL B	No.Occ	LEVEL C	No.Occ	LEVEL D	No.Occ
Brown Stair	15	Red Stair	23	Exit 10	67	Exit 9	7
Red Stair	10	Blue Stair	17			Blue Stair	17
Blue Stair	9	Green Stair	5			Green Stair	5
Green Stair	1					Blue Stair	4
						Fire Stair	2
LEVEL E		LEVEL F		LEVEL G			
Exit 6	16	Exit 2	0	Exit 1	2		
Red Stair	12	Exit 3	5				
Green Stair	1	Exit 4	19				

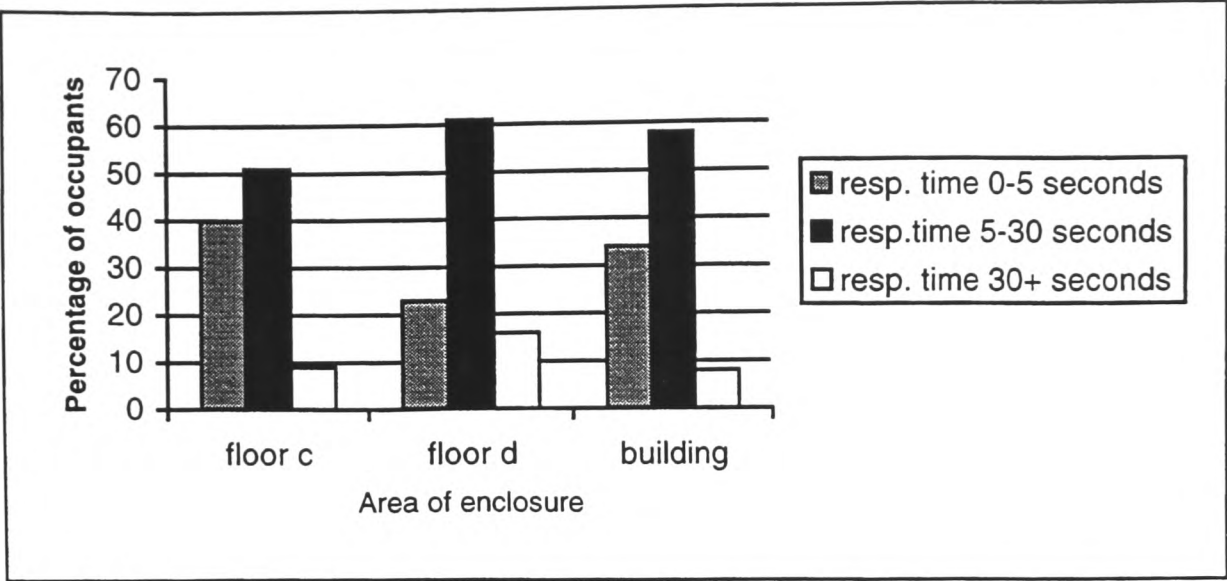
TABLE 4-7: EVACUATION TIMES FOR EACH EXIT AS REPORTED BY THE OBSERVERS [196].

\* indicates that two times were incorrectly recorded for this exit.

Exit Number	# of people observed to use exits.	# of people responding to questionnaire	First Exit (seconds)	Last Exit (seconds)
1	2	2	45	45
2	6	0	25	48
3	6	5	80	90
4	40	19	45	105
5	0	0	-	-
6	23	16	21	115
7	0	0	-	-
8	48	15	34	190
9	8	7	22	90
10	248	67	22	220*(286)
Total Exited	381			220 (286)

4.23.3 RESPONSE TIMES.

As part of the questionnaires, participants were requested to estimate their response times. The response times were categorised into three intervals, 0 - 5, 5 - 30 and 30+ seconds. Unfortunately, a high degree of ambiguity exists in the 30+ category as no upper bound was specified. Furthermore, information of this type is highly unreliable when it is gathered directly from evacuation participants. Response time data as collected from the questionnaires is presented in Figure 4-5.



**FIGURE 4-5: RESPONSE TIME DISTRIBUTION FOR FLOORS C, D AND THE ENTIRE BUILDING.**

Examining the motivation behind the response of occupant’s on floor D [196], we find that 94% of the occupants began to evacuate on actually hearing the alarm message. The remaining occupants are assumed not to have responded to the alarm but to other triggering mechanisms such as communication with other occupants. This type of response was distributed throughout floor D with no region being identified as not being able to hear the alarm. Of those occupants returning a questionnaire on floor D, 71% claimed to have responded immediately. However their interpretation of the word ‘immediately’ differed, ranging from responding after 0-5 seconds to 30+ seconds, invalidating the question. The rest of the occupants (29%) performed some action prior to leaving; this might have been business related or safety related.

**4.23.4 GENERAL COMMENTS CONCERNING TRIAL RESULTS.**

Several comments can be made concerning the results produced from this trial.

- Considering the size of the building, only a very small population actually took part in the evacuation.
- The high use of Exit 10 is thought to be due to the location of the assembly point - which was located by the exit. A number of people from other floors made use of Exit 10, not simply those from floor C. The observers at Exit 10 described considerable blockages and delays due to the large numbers of occupants attempting to use this exit [196].
- People on floors A, E, F and G generally moved towards the nearest exit [196].
- On floor B, 53% of the evacuees initially attempted the ‘fire’ stair. It was assumed that a proportion of the occupants who did not try the ‘fire’ stairwell had prior communication with occupants moving away from the ‘fire’ stairwell [196].
- People on floor D displayed the most complex behaviour seen in the trial. Occupants moved toward all of the available stairwells/exits, both ascending and descending to

different floors. Occupants even attempted to ascend via the fire exit. The majority of these turned back once they had seen the 'fire' sign, however, two continued through the staircase and exited via the fire exit [196].

- There are a number of discrepancies between the figures recorded by the observers and the data generated from the questionnaire, e.g. exact position of occupants, number of occupants. Several discrepancies also exist in the evacuation times recorded by the observers.
- The arrival of occupants from other floors may distort the distribution of times at exit 8 (situated on floor D). Floor D originally contained 48 occupants.

#### 4.24 SPECIFYING THE BUILDINGEXODUS SIMULATIONS.

As explained in section 4.13.1, before using buildingEXODUS to run the various simulations it is necessary to specify the precise nature of the geometry and the population. This includes a description of the staircases. Unfortunately, no such description is provided in the report [193, 196]. *Thus, rather than make arbitrary assumptions concerning the stairwell geometry, the validation exercise will be limited to situations in which stair usage can be ignored.* Furthermore, due to the sparseness of the population, the lack of detailed data concerning the paths taken by the occupants, and the times of movement in reference to staircases and certain exits, *only the evacuation of occupants from specific areas will be attempted in this validation exercise.* Finally, due to the complexity, incompleteness and ambiguity of the data set, this validation can only be considered, at best as a qualitative validation where full prior knowledge of the available data is assumed.

##### 4.24.1 SPECIFICATION OF THE GEOMETRY

After close examination of the available data, Floor D was chosen for simulation. While floor D has a low questionnaire response rate, it has a number of available exits and hence the potential for relatively complex occupant behaviour. As the entire structure is not simulated, stairwells found on floor D are treated as exit points for those occupants on floor D. In total, floor D possessed seven possible exit points (exits 7 (not used), 8 and 9 and stairs green, blue, red and fire). This allowed the effects of familiarity and exit availability to exert an influence over the observed egress behaviour.

The enclosure was generated within buildingEXODUS from the original floor plans. These had been scanned and resized using a CAD facility to generate a DXF description (see Figure 4-3). Exit dimensions are estimated from examination of the floor-plans.

However, inaccuracies in exit sizes resulting from the scaling procedure are expected. These are not expected to adversely effect predicted evacuation times due to the sparsity of the populations and distribution of response times considered in this exercise.

Finally, while buildingEXODUS is capable of including obstacles such as furniture, these items are ignored, as no details are available [193, 196].

#### 4.24.2 SPECIFYING THE POPULATION

No information is available concerning the occupant details. It is not clear if the occupants who took part in the test comprised people who had a good working knowledge of the building or if occasional users of the building were present.

Of the information that was available, missing or conflicting data relating to occupants on floor D reduced the number of people which could be analysed. This meant that of the 40 occupants claimed to have returned questionnaires, only 36 could be used. Again given the distribution of the occupants throughout the enclosure and the nature of the response times, this was not expected to have a significant impact.

The vagueness of the data set makes it difficult to justify its use for quantitative validation. Rather it will be used primarily for qualitative validation. In addition, the Milburn House evacuation trial will be used to examine the influence of those factors that, although supplied, leave large margins for error. These include response times and occupant starting locations. As no information was provided concerning the occupants make-up, assumptions have to be made, and the effects manipulating the occupants within these assumptions are examined. These assumptions will be examined in the different cases presented in the section describing the scenarios investigated (see section 4.23.3).

In general the population will be randomly generated with buildingEXODUS assigning attributes for typical 'office' scenarios, i.e. ages ranging between 25-55 years, equal distribution of males and females. No occupants with disabilities will be included as none were reported to be present. Where "reported response times" are indicated this will be taken to be the occupant starting times generated using distributions within the limits reported, namely 0-5 seconds, 5-30 seconds and over 30 seconds. Occupant responses are assumed to be evenly distributed throughout the two bounded categories.

The upper limit for the 30+ category will be assumed to be 40 seconds unless otherwise stated.

Unless stated otherwise, the maximum travel speed for population members will assume the default distribution of 1.2 – 1.5 m/s. Likewise, the drive distribution will assume the default spread of 67% (see section 4.23.1). Finally, unless otherwise stated, the population on floor D comprises 36 people, while the population of floor C comprises 67 people.

#### 4.24.3 THE SCENARIOS

Due to the vagueness of the problem specification a number of different scenarios are investigated. These involve varying population physical parameters, population behaviour parameters and population starting locations.

The variation in population behaviour investigated concerns response times and the nature of exit selection. Two main response time scenarios are considered, namely, the population responds immediately (i.e. zero response time) and the population adopts the actual response time as indicated in section 4.23.3. Several exit selection cases are examined involving the selection of the nearest exits (i.e. no exit bias), the selection of biased exits (i.e. imposing biasing extracted from the questionnaires indicating exit usage during the evacuation) and the imposition of target exits imposed (i.e. occupants are assigned an exit).

All exits will make use of free-flow flow rates. Also, within a given floor, the precise starting location of the occupants is not known. An arbitrary starting location is assumed and used for all the simulations unless otherwise stated. In some cases, the starting location of occupants within a particular room is randomised in order to demonstrate the effect this may have on the predictions.

The 'non-emergency' nature of the evacuation drill suggests that the 'NORMAL' operation regime is most appropriate to use for these simulations. To summarise, the following scenarios involving Floor D are investigated:

- D1.No exit bias, zero response times, uniform speed.
- D2.No exit bias, actual response times, uniform speed.
- D3.Exit bias, actual response times, uniform speed.

- D4.Exit bias, actual response times, uniform speed, fire exit effect.
- D5.Exit bias, actual response times, speed distribution.
- D6.Exit bias, actual response times, speed distribution, fire exit effect.
- D7.Target doors imposed, actual response times, speed distribution.
- D8.As D7 with systematic randomisation of occupant location (D8a) and with systematic randomisation of the occupant response times (D8b)
- D9.As D7 with extension of the response time upper limit from 40s to 90 and 120s.

#### **4.25 THE BUILDINGEXODUS PREDICTIONS OF THE MILBURN HOUSE EVACUATION TRIALS.**

In the proceeding sections results of the buildingEXODUS predictions for the Milburn House evacuation trial for floor D are presented. Each of the buildingEXODUS predictions presented below represent the average of five repeated simulations, unless otherwise stated. This is done in an attempt to accommodate the natural variation in model predictions. However, in cases involving little or no occupant interaction, buildingEXODUS is unlikely to generate any significant variation in occupant performance.

All the simulations presented in this section were carried out using a Pentium 133 MHz PC with 32 MB of RAM. Each simulation was completed in less than 10 minutes. The floor D simulations required approximately seven minutes to compute, while the floor C simulations required slightly longer due to the larger population. These times include the time required to load the geometry into the computer.

##### **4.25.1 THE BUILDINGEXODUS PREDICTIONS**

###### **(I)CASE D1**

A difficulty arises when attempting to compare model predictions with trial results for the occupants on floor D. While the observers measured the time for the first and last arrival at exits 8 and 9, no equivalent time is measured for the staircases. This is because no observers were positioned at these locations.

The first case considered is the control Case D1. In this case we assume that all the occupants use their nearest exits, travel with uniform speed and have zero response time. The assumptions made here are similar to what may be found in traditional prescriptive building codes.

From Table 4-8, it is apparent that buildingEXODUS significantly *under*-predicts the time for the first and last people out of each exit. Most importantly, the lower boundaries



of these evacuation times – i.e. the time for the first person out - are lower than those produced in the actual event. This is significant, as we would expect the model predictions for the time of the first person out to be less affected by the impact of additional undocumented occupants than the time for the last person out.

It is clear from the outcome of this simulation that the assumptions inherent in Scenario D1 are inappropriate.

**TABLE 4-8: BUILDINGEXODUS PREDICTIONS FROM SCENARIO D1. PARENTHESES INDICATE ACTUAL MEASURED RESULTS.**

Exit	Time for first occupant out (sec)	Time for last occupant out (sec)	number out
Red	10.8	24.2	14 [12]
Brown (exit 9)	2.9 [22]	17.8 [90]	6 [6]
Blue	9.4	26.9	9 [4]
Black (exit 8)	12.7 [34]	18.9 [190]	3 [12]
Orange (fire)	10.4	23.8	4 [2]

**(ii)Case D2**

For this simulation, the actual response times retrieved from the questionnaires are applied to the occupant population (Scenario D2). All other attributes are identical to those of Scenario D1. The results for this simulation are presented in Table 4-9.

**TABLE 4-9: BUILDINGEXODUS PREDICTIONS FROM SCENARIO D2. PARENTHESES INDICATE ACTUAL MEASURED RESULTS.**

Exit	Time for first occupant out (sec)	Time for last occupant out (sec)	number out
Red	12.1	50.6	14 [12]
Brown (exit 9)	18.5 [22]	46.9 [90]	6 [6]
Blue	19.3	54.2	9 [4]
Black (exit 8)	35.0 [34]	55.2 [190]	3 [12]
Orange(fire)	47.6	53.8	4 [2]

Clearly, the imposition of response times has a significant impact on the predicted results (see Table 4-9). The significance of including response times can be determined by comparing Table 4-8 with Table 4-9. The evacuation times in Table 4-9 have increased on average by 189% compared with those in Table 4-8. It is also clear that on average the time of the first occupant out are proportionately more significantly affected than the time for the last person out. Furthermore, not all the exits are affected to the same degree. This is because a number of the first occupants to arrive at certain exits have small response times (0-5 seconds) while at other exits, the first person to arrive has a relatively long response time (30-40 seconds). It should be recalled that the starting locations for all the occupants in both scenarios are identical.

A number of other observations can be made concerning these results. Firstly, an overuse of the orange exit (the fire exit) is evident in both simulations. This is a result of scenario specific assumptions concerning the exit usage. It was assumed in these scenarios that all exits were equally attractive.

The inclusion of response times does not result in a simple offset to the evacuation times. A complex interaction exists between response times and exiting times.

There appears to be a good correlation between the predicted and observed time for the first arrivals at exits 8 and 9. This is to be expected as the closest recorded occupants to these exits used them during the actual evacuation. This feature is consistent with the scenario assumption that occupants use their nearest exit.

In the model predictions, exit 8 is significantly underused. This is likely to be due to the dispersed nature of the population that actually used this exit during the evacuation trial and the isolated positioning of the exit itself. This suggests that while some occupants used their nearest exits, globally this was not the case for everyone.

### **(iii) Case D3**

Within buildingEXODUS it is possible to bias an exit, making it more or less attractive. This is achieved by assigning the exit weighting known as the “exit bias”. As the potential map is derived from these exit weightings, its desirability and therefore its catchment area will be affected (see Chapter 3). This biasing may represent a number of factors, such as for example the use of signage or occupant familiarity.

The next simulation examines the use of “exit bias” in an attempt to increase/decrease exit usage. The exits are biased in an attempt to reflect their actual usage during the evacuation trial. While there are many ways in which this can be achieved, in this case it is attempted by ranking the attractiveness of the various exits by the degree of actual usage. While the actual usage rates would not have been available for modelling purposes in a ‘blind’ validation, it is useful to use this information to demonstrate the flexibility of the present buildingEXODUS model. The results of this scenario are presented in Table 4-10. The most notable outcome of this scenario is that the biasing has successfully reproduced the usage of the orange (fire) stair.

TABLE 4-10: BUILDINGEXODUS PREDICTIONS FROM SCENARIO D3. PARENTHESES INDICATE ACTUAL MEASURED RESULTS.

Exit	Time for first occupant out (sec)	Time for last occupant out (sec)	Number out
Red	12	52	14 [12]
Brown(exit 9)	18.6 [22]	46.0 [90]	6 [6]
Blue	19.0	54.21	10 [4]
Black (exit 8)	28.8 [34]	55.1 [190]	4 [12]
Orange (fire)	48.9	49.4	2 [2]

While a useful device for modifying exit usage, the exit bias will only influence occupants within the catchment area of the biased exit. Thus occupants that are far removed from an exit are unlikely to be influenced by the exit bias. In the sparsely populated floor D, this is indeed the case, as only two occupants were affected by the exit biasing.

(iv)Case D4

Another useful feature of buildingEXODUS is the capability to represent the opening and closing of exits during an evacuation. This allows the user to simulate the availability of exits, and the changing status of exits during the evacuation. In addition, an exit can be made active or inactive. An inactive exit will not attract occupants whether the exit is open or closed, whereas an active exit has the ability to attract occupants whether open or closed. A closed exit that is active will still attract occupants who find that they cannot use the exit. This is intended to simulate the situation in which occupants do not have information concerning the usability of the exit. If a closed exit is inactive, occupants will not be attracted to the exit.

This feature is implemented in D4, where the ‘fire’ exit will close and be inactive after 40 seconds. This is intended to represent the situation in which an unusable exit does not attract occupants due to, for instance the possibility of occupants communicating information concerning the existence of a blockage. In all other respects, scenario D4 is identical to D3.

It should also be noted that when the exit status changes to closed and inactive, the potential map is altered. Occupants will therefore be diverted from their original paths.

The results for simulation D4 are presented in Table 4-11. The number of people using the fire exit has decreased to zero. From Table 4-10, the first person to use the fire exit

exited after 48 seconds. As the exit becomes inactive after 40 seconds, this person will be diverted away from the exit.

TABLE 4-11: BUILDINGEXODUS PREDICTIONS FROM SCENARIO D4. PARENTHESES INDICATE ACTUAL MEASURED RESULTS.

Exit	Time for first occupant out (sec)	Time for last occupant out (sec)	number out
Red	12	52.0	14 [12]
Brown (exit 9)	18.6 [22]	71.8 [90]	8 [6]
Blue	19.0	54.2	10 [4]
Black (exit 8)	28.8 [34]	55.2 [190]	4 [12]
Orange	0	0	0 [2]

The effect of this diversion can be highlighted using the *Path* facility. This feature allows individual paths taken by occupants to be traced out on the floor plan. Figure 4-6 shows the path of an occupant originally moving towards the fire exit who diverts on learning that the exit is not usable.

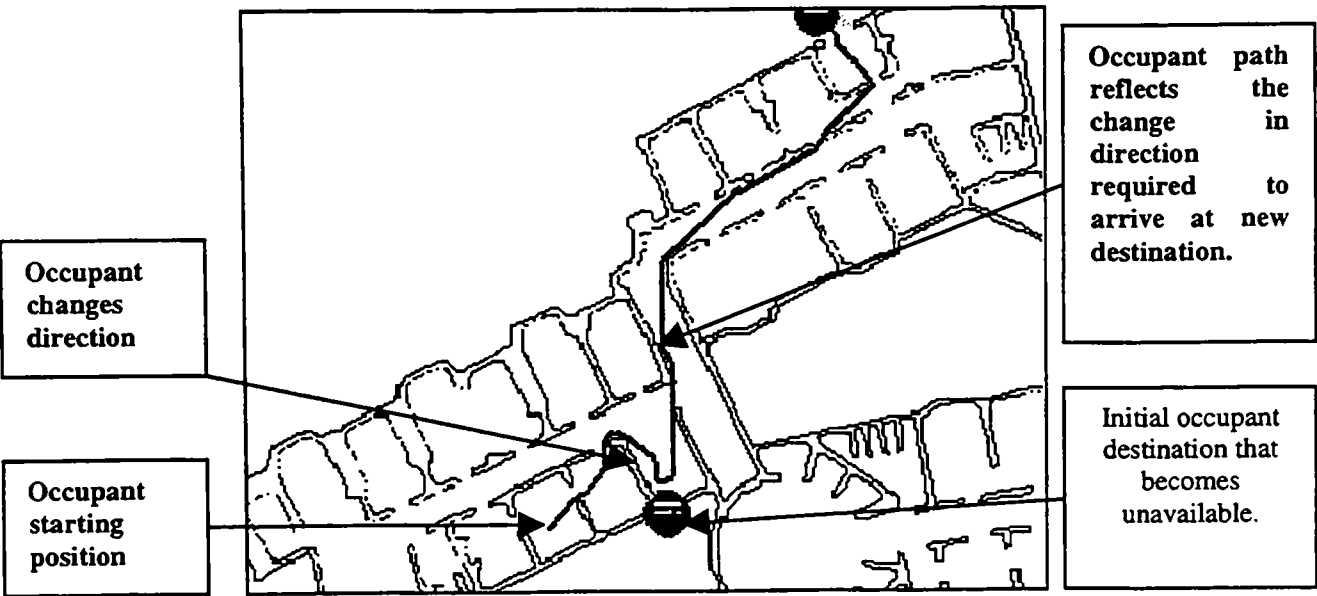


FIGURE 4-6: BUILDINGEXODUS GENERATED OCCUPANT PATH FOR AN INDIVIDUAL WHO IS ATTRACTED TO THE FIRE EXIT AND THEN DIVERTED TO ANOTHER EXIT.

(v)Case D5

In all the simulations to date, occupants were assigned identical maximum uniform travel speeds of 1.5 m/s. In this scenario the occupants are randomly assigned maximum travel speeds between 1.2 and 1.5 m/s (i.e. the default speed distribution for randomly generated occupants). All other scenario parameters are identical to those found in scenario D3. The results for this simulation are found in Table 4-12. As may be expected, the evacuation times for scenario D5 are slightly longer than those found in scenario D3, with an average increase of 5.5% (see Table 4-10).

TABLE 4-12: BUILDINGEXODUS PREDICTIONS FROM SCENARIO D5. PARENTHESES INDICATE ACTUAL MEASURED RESULTS.

Exit	Time for first occupant out (sec)	Time for last occupant out (sec)	number out
Red	13.7	52.9	14 [12]
Brown(exit 9)	20.9 [22]	49.0 [90]	6 [6]
Blue	19.3	55.9	10 [4]
Black(exit 8)	30.4 [34]	57.4 [190]	4 [12]
orange(fire)	50.5	51.7	2 [2]

(vi)Case D6

The limited availability of the fire door is now introduced into the specification of scenario D5. As in scenario D4, access to the fire stair is prohibited after 40 seconds.

TABLE 4-13: BUILDINGEXODUS PREDICTIONS FROM SCENARIO D6. PARENTHESES INDICATE ACTUAL MEASURED RESULTS.

Exit	Time for first occupant out (sec)	Time for last occupant out (sec)	number out
Red	14.1	53.3	14 [12]
Brown(exit 9)	20.9 [22]	73.8 [90]	8 [6]
Blue	19.3	57.6	10 [4]
Black (exit 8)	31.1 [34]	58.8 [190]	4 [12]
Orange(fire)	0	0	0 [2]

Comparing the results for scenario D6 (Table 4-13) with those of scenario D4 (Table 4-11) we again find that the introduction of a range of maximum travel speeds increases the predicted evacuation times (average increase of 5.8%).

These changes highlight the necessity of imposing a travel speed distribution rather than a uniform constant travel speed.

(vii) Case D7

In the next simulation (scenario D7) occupants are assigned target exits. Within buildingEXODUS it is possible to direct occupants to a target exit, effectively side-stepping the direct impact of the potential map. In this way, the global behaviour of each occupant can be controlled by their desire to attain the goal of the target exit. It should be noted that when target exits are specified, the local behaviour and local navigation procedures are still enforced.

With the exception of specifying target doors, scenario D7 is identical to scenario D5. In this simulation, the target doors are assigned with knowledge of the exit usage achieved in the actual trial. Given the limited information available, the results from this scenario

should provide the best agreement with trial results. The results for scenario D7 are presented in Table 4-14.

**TABLE 4-14: BUILDINGEXODUS PREDICTIONS FROM SCENARIO D7. PARENTHESES INDICATE ACTUAL MEASURED RESULTS.**

Exit	Time for first occupant out (sec)	Time for last occupant out (sec)	Number out
Red	14.1	52.8	12 [12]
Brown (exit 9)	20.9 [22]	49.5 [90]	6 [6]
Blue	19.3	54.2	4 [4]
Black (exit 8)	30.4 [34]	93.8 [190]	12 [12]
Orange (fire)	50.5	51.7	2 [2]

As expected, the predicted number of occupants arriving at each exit is identical to that recorded during the trial. In addition, the predicted times for the first occupants out of exits 8 and 9 are relatively close to the recorded evacuation times (differences of 10.1% and 5% between measured and predicted values for exits 8 and 9 respectively).

**(viii) Case D8**

The results in Table 4-14 form the basis of an analysis that demonstrates the sensitivity of model predictions against both the uncertainties in the data set and the natural variation in certain model parameters. This analysis is performed to emphasis the importance of correctly characterising experimental data intended for quantitative validation of evacuation models.

The primary parameters to be considered in this type of analysis consist of the starting location of the occupants, the response time categorisation of the occupants and the precise capability of each occupant. For the purposes of this study only the first two parameters are considered (scenario D8).

In the Milburn House data set, the precise starting location of the occupants was not specified. However, a crude measure was provided by marking on an unscaled diagram the starting location of individuals. In essence this narrowed down the location of individuals to compartments within the enclosure. However, as the compartments were quite large and the population quite small, inaccuracies in model predictions may result from this level of approximation.

To demonstrate this, the location of the occupants within their given compartment is randomised to reflect the uncertainty in starting location (scenario D8a). This change in occupant location is achieved using the buildingEXODUS *Randomise* facility that

enables the re-location of selected occupants within a specified area. It should be noted that the randomisation procedure does not alter any of the population parameters other than the occupant starting location.

The randomisation procedure was repeated 3 times. In addition, the evacuation simulation for each starting location was repeated five times. The results for the D8a scenario are presented in Table 4-15. The evacuation times presented in Table 4-15 represent simulation averages. Those times in square brackets represent the range in averages for each starting location, while the single time represents the average evacuation time over all the simulations.

We note from Table 4-15 that there is a significant distribution of mean evacuation times. The range in mean evacuation times for the first person out is as large as 26.2% (exit 9) with an average spread of 16%. Thus, if the precise location of occupants are not known, model predictions for the time of the first person out (i.e. the most reliable model predictions in this case) can be expected to display as much as a 26.2% variation.

TABLE 4-15: BUILDINGEXODUS PREDICTIONS FROM SCENARIO D8A.

Exit	Time for first occupant out (sec)	Time for last occupant out (sec)	Number out
Red	14.3 [13.0 - 15.1]	52.9 [51.3 - 54.2]	12
Brown (exit 9)	19.8 [18.0 - 23.1]	47.3 [45.8 - 48.5]	6
Blue	21.6 [19.1 - 22.5]	54.3 [53.5 - 55.9]	4
Black (exit 8)	34.4 [30.0 - 36.2]	99.9 [97.1 - 102.9]	12
Orange (fire)	52.9 [50.0 - 53.0]	53.9 [51.1 - 54.6]	2

In the Milburn House data set, the precise response time of the occupants was not specified. However, a crude measure was provided by categorising the possible response times into broad non-uniform categories (i.e. 0-5 seconds, 5-30 seconds and 30+ seconds). Although this categorisation provides some indication of the occupant response times, it does introduce a substantial degree of uncertainty into the model predictions.

To demonstrate this effect, individual occupant response times are randomised within the specified boundaries. This was achieved by allowing the occupants to remain in their

original starting location whilst maintaining all other attributes, but altering their response time attribute (scenario D8b).

This procedure was repeated five times. The results for these simulations are presented in Table 4-16. The evacuation times presented in Table 4-16 represent simulation averages. Those times in square brackets represent the range in averages for each response time assignment, while the single time represents the average evacuation time over all the simulations.

We note from Table 4-16 that there is a significant distribution of mean evacuation times. The range in mean evacuation times for the first person out is as large as 86% (exit 9) with an average spread of 66%. Thus, if the precise response times of occupants are not known, model predictions for the time of the first person out can be expected to display as much as 86% variation. The average variation for the last person out is 24%. In general, the evacuation time for these occupants has a greater contribution from the travel time than does the first person out.

**TABLE 4-16: BUILDINGEXODUS PREDICTIONS FROM SCENARIO D8B.**

Exit	Time for first occupant out (sec)	Time for last occupant out (sec)	Number out
Red	13.9 [9.1-16.1]	51.1 [42.1-56.2]	12
Brown (exit 9)	19.9 [14.1-26.2]	47.1 [41.0-51.3]	6
Blue	20.1 [13.4-24.1]	52.1 [42.4-56.1]	4
Black (exit 8)	31.2 [22.3-34.2]	97.1 [88.2-102.2]	12
Orange (fire)	49.6 [43.0-57.1]	52.1 [40.1-58.1]	2

**(ix)Case D9**

The final scenario to be investigated concerns an examination of the open-ended upper bound to the occupant response times. In the trial questionnaire, the upper bound for the occupant response time was simply stated to be 30+ seconds. In the simulations presented thus far, this occupant response time category was arbitrarily set as 30 – 40 seconds. In these simulations (scenario D9), the upper bound of the 30+ category is altered from 40 seconds to 90 and 120 seconds. With the exception of changing the upper limit of response times, scenario D9 is identical to D7. The results for these simulations are presented in Table 4-17.



As can be noted from Table 4-17, the time of the first person out is not greatly affected by the increase in the upper limit of the response time for the 30+ category. This is because the first occupants to leave the enclosure generally have the shorter response times and are therefore not influenced by alterations to the 30+ category. The exception to this are the results produced for the orange (fire) exit point. This is because both of the occupants using this exit had response times in excess of 30 seconds.

In contrast, the time for the last occupant out increases significantly in proportion to the increase in response time. However, the blue stairwell is not effected by this trend. This is due to these occupants not being in the 30+ category.

TABLE 4-17: BUILDINGEXODUS PREDICTIONS FROM SCENARIO D9.

Exit	30-40		30-90		30-120		No. of Occ
	1 <sup>st</sup> occ out (secs)	Last occ out (secs)	1 <sup>st</sup> occ (secs)	Last Occ Out(secs)	1 <sup>st</sup> occ out (secs)	Last Occ Out(secs)	
Red	14	53	14	97	14	101	12
Brown (exit 9)	21	50	21	96	21	114	6
Blue	19	54	23	56	23	56	4
Black (exit 8)	30	94	30	107	30	138	12
Orange (fire)	51	52	105	105	118	127	2

4.3 THE TSUKUBA DATA-SET

During the 1985 Tsukuba exposition [194], observations were made of people leaving seven different pavilions. The behaviour of occupants was filmed using portable video cameras. The cameras were positioned to capture occupant behaviour around the exits. Due to the nature of the Tsukuba Exposition, the researchers had the opportunity to record several “evacuations” of the pavilions. Each such event involved a different audience. Hence a range of “evacuation times” are provided. Concerning the use of the term evacuation, it is not clear whether or not the audiences were aware that an “evacuation” or even an “evacuation trial” was underway. It is only reported that the audiences were instructed to leave the pavilions by a conductor.

4.31 THE PAVILION GEOMETRIES

The geometric details of the seven pavilions are provided in the original report (see Table 4-18) [194]. The pavilions differed in terms of, shape, dimensions, seating capacity, internal layout (i.e. seating arrangement) and style of seating (including benches and flip-up seats).

TABLE 4-18: DETAILS OF TSUKUBA EXPO PAVILIONS [194].

Pavilion I.D.	Capacity	Theatre floor area (m <sup>2</sup> )	Number of exits	width (m)
FR	1000	1014	12	20.4
SH	500	563	7	12.6
SU	424	540	7	15.4
TO	508	693	12	16.2
ST	366	682	8	16.0
NT	350	452	10	14.0
TD	405	401	5	9.6

Within the report, floor plan diagrams are provided only for the SH (see Figure 4-7) and FR pavilions. This omission prevents the modelling of the other pavilions. Thus, for the purposes of this paper, only the SH pavilion was selected for simulation.

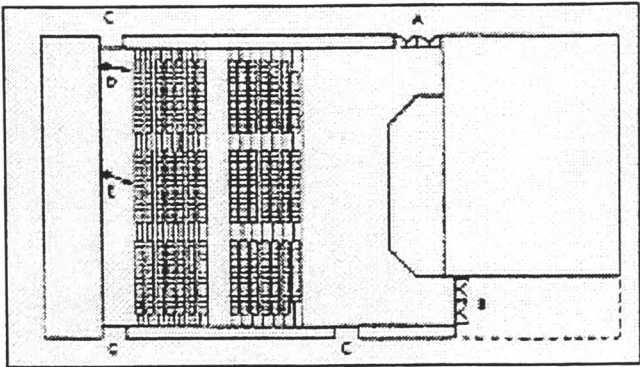


FIGURE 4-7: THE SH TSUKUBA PAVILION [194].

4.32 THE OCCUPANTS

Little information concerning the make-up of the occupants is provided in the original report, other than the occupants were from the ‘theatre-going’ public [194]. The occupant population taking part in each of these evacuations are, however, assumed to be different, due to the nature of the exhibition described in the report [194].

No information is provided concerning the response times, occupant capabilities or starting location. In addition, no information is provided concerning the exact number of occupants taking part in the ‘evacuation’, only the capacity of each pavilion.

It is not clear as to the level of audience awareness of the evacuation or the ‘seriousness’ with which the incident was considered. The ‘conductor’ (who gave the message) may have instructed the occupants of the next event, or may have informed them of the need to evacuate. The manner in which these instructions were delivered would have had an effect on the response time of the occupants [103,142]. Furthermore, while the term “evacuation” is used in this paper to describe the event, as the exact message given to the occupants is not known, it is not possible to ascertain whether the occupants considered it as such.

The incentive for the movement of audiences between shows was concerned with the desire to visit several pavilions. This acted as a form of motivation during the evacuation and was considered to be more forceful than the normal desire to visit events due to the tight exposition schedule. The short duration of the shows (between 30-60 minutes) enabled a number of evacuations to be recorded.

Kose et al, noted the presence of disabled/less-able occupants during the various evacuations [194]. Unfortunately, the events which included the less-able amongst the audience are not identified. However, the less-able members of the audience are not expected to exert a significant influence on the evacuation times as they were effectively excluded from the data set. It is noted in the Tsukuba evacuation report:

*“The exit time of wheelchair users who happened to be in the theatre was excluded from the analysis because they generally get out after the queues disappeared to avoid congestion.”* [194].

However, it is unclear whether the disabled occupants delayed any of the other occupants during the evacuation.

#### **4.33 EVACUATION RESULTS**

Four evacuations of the SH pavilion were recorded. These produced evacuation times of 160, 152, 166, and 157 seconds resulting in an average evacuation time of 158.8 seconds. One double door, measuring 3.6 m in width, was used for the egress of the occupants. The occupants entered the auditorium via the front left door (as viewed by someone facing the stage) and departed via the front right door (see Figure 4-7). Only the time for the last person out was recorded. This prevents any detailed quantitative comparison between model predictions and measured results to be made other than with the final egress time. The time taken for occupant egress was measured from a message given by the conductor. Kose et al, noted that the general consistency between measured results suggested confidence in the quality of the observations [194].

In addition to the quantitative results reported above, some qualitative remarks were also made. The researchers noted that the audience utilised the spaces in-between the rows of seats as egress routes.

Furthermore, and quite significantly, delays and blockages at the exit were observed during the SH evacuation. This was not the result of structural or evacuation procedural weaknesses, but to the inclement weather conditions. (a similar effect was also noted in

Ohio concert incident relating to inclement weather conditions[197]) This specifically affected the SH pavilion as its exits opened directly to the outside, exposing the occupants to the rain. Clearly, this effect should be taken into consideration when attempting to simulate the SH evacuation.

#### **4.4 ATTEMPTS AT SIMULATING THE TSUKUBA EVACUATION**

Several attempts have been made to compare the Tsukuba evacuation times with calculated predictions. The Kose predictions [194] were based upon the method of Predtechinskii and Milinskii [150]. The enclosure was assumed to be composed of a number of coarse blocks with occupants being assumed to respond instantly. These results underestimate the actual evacuation time by approximately 31%. The Ketchell et al predictions [20] were based on the EGRESS evacuation model [18,19]. These were based on the assumption that 450 occupants were situated in the auditorium. Under these circumstances, the EGRESS predictions under-predict the actual results by some 17%. Ketchell et al account for this difference due to the inability of EGRESS to deal with the occupants decision not to leave the building due to the inclement weather conditions [20].

#### **4.5 THE BUILDINGEXODUS PREDICTIONS**

buildingEXODUS was used to simulate the SH pavilion evacuations. A number of different simulations were performed to investigate both the inherent capabilities of the software and its ability to predict the outcome of the evacuation. In this section we define the simulations (i.e. geometry, population and scenarios) and present the results.

##### **4.51 SPECIFYING THE BUILDINGEXODUS SIMULATIONS.**

Before buildingEXODUS can be used to run the various simulations it is necessary to specify the precise nature of the geometry and the population. Thus the SH pavilion geometry must be specified in detail if an accurate prediction of the experimental results is to be achieved. As there are several ways in which this can be done it is essential to clearly specify the geometry and population. This will in turn define the nature of the scenarios simulated.

##### **4.51.1 SPECIFYING THE GEOMETRY**

The geometry and layout of the SH pavilion is depicted in Figure 4-8. This figure forms the basis of the buildingEXODUS representation of the geometry. Within the buildingEXODUS model, seating is arranged as shown in Figure 4-8 and the exit is located in the same position. Only a single exit, 3.6m in width is provided and the total floor area is known to be 563 m<sup>2</sup>. Unfortunately, the exact dimensions of the floor area are not provided. From the diagram supplied in the report, the dimensions of the pavilion are estimated to be 25m x 23m at its widest point.

Within buildingEXODUS the seats are modelled as blockages. As noted in the original experiments, movement along seat rows was observed. This movement is allowed within the buildingEXODUS model.

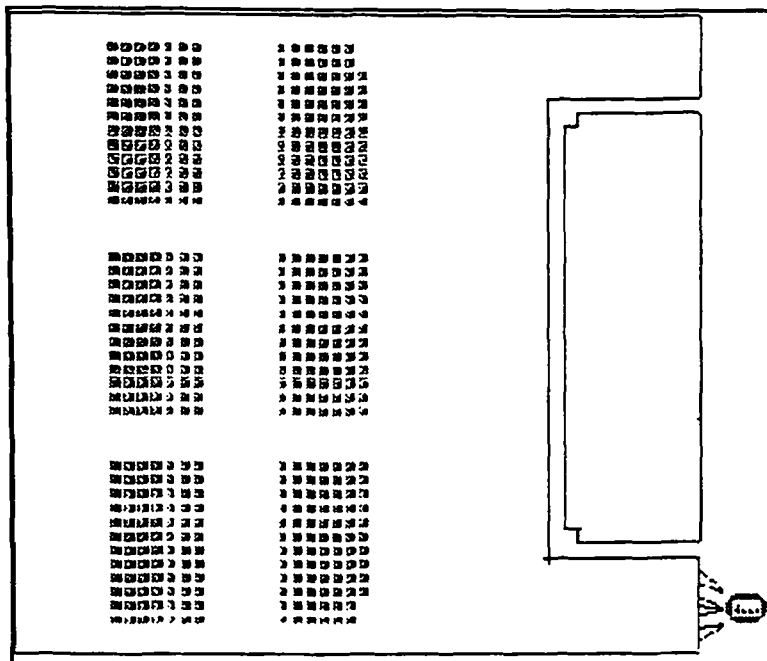


FIGURE 4-8: THE BUILDINGEXODUS REPRESENTATION OF THE SH PAVILION.

As described in Section 4.13.2, within buildingEXODUS an important parameter used to describe the flow capabilities of an exit is the exit flow rate. In the simulations presented in this paper, each of the above options will be tested.

#### 4.51.2 SPECIFYING THE POPULATION

The SH pavilion evacuation appears to have been conducted under “normal” or “non-panic” conditions. Thus, the buildingEXODUS simulations used the NORMAL behaviour option and hence it is not necessary to set the *PATIENCE* attribute for the occupants. A capacity audience of 500 occupants is assumed in all the simulations. In addition, as the evacuation is not considered to be under emergency conditions, the simulated occupants are not permitted to jump over seats and hence the *AGILITY* attribute is not required.

In buildingEXODUS, with the exception of prescribing default travel speeds on stairs, the gender and age attributes are descriptive in nature and are used as a guide to setting other personal attributes. Hence the simulations presented here will not be sensitive to the age and gender distributions. Without any additional information, the maximum *TRAVEL SPEED* distribution for the population assumes the default setting of 1.2 - 1.5 m/s. This speed range is used when occupants are moving on free open space. When travelling between the seat rows, the maximum *TRAVEL SPEED* assumes the distribution 1.08–1.35 m/s.

Within buildingEXODUS conflicts are resolved through comparison of the occupant attribute *DRIVE*. If the population is given a uniform drive, its members are considered to be equally motivated and highly competitive. Each conflict would be contested by equally matched individuals, who were not prepared to let the other by. Within buildingEXODUS this would result in long delays, as each conflict would need to be randomly resolved. If the population is made up of people with differences in their drives, conflicts will be resolved more quickly and incur less delays, resulting in a smoother evacuation.

The evacuation population was made up of the general (theatre going) public. Under normal conditions where a diverse population can be expected, the default setting for the *DRIVE* distribution should be used. This results in a *DRIVE* distribution of some 67%. This effectively results in the normalised difference between the population maximum and minimum drives being 67%. The impact of manipulating the *DRIVE* setting in evacuation simulations is examined more extensively in another publication [27].

Another important population attribute is the *RESPONSE TIME* for each individual. This is the time elapsed between the start of the evacuation and the time the individual begins to actively evacuate i.e. move towards an exit. While the response times for the occupants are expected to be small – due to the incentive to move on to the next pavilion – it is unlikely to be zero seconds for the entire audience. Normally a response time distribution would be imposed on the population. In the simulations presented here, a range of response time distributions are investigated. These comprise a uniform 0 seconds response time, and distributions of 0-30 seconds, 0-60 seconds, 0-90 seconds and 30-90 seconds.

#### **4.51.3 SPECIFYING THE SCENARIOS.**

For each case investigated a new population is generated. However, the upper and lower limits that are used to specify the range of population attributes are identical in each case. Thus, while buildingEXODUS will generate a different random mix of people for each simulation, the range of population attributes in each case is identical.

In each scenario, the population is initially located within the seating area. Each scenario is repeated three times with occupants assuming different seating positions. This is then repeated with a different randomised population. Therefore each scenario is repeated six times in total in order to produce the range of predicted evacuation times. An average evacuation time for each scenario is also generated.

Essentially two types of scenario are performed. The first ignore the effects of the inclement weather conditions, whereas the second take these conditions into consideration. In addition, some of the scenarios are intended to demonstrate the impact of certain features within the buildingEXODUS software. The scenarios investigated are:

Scenario 1:

- Response time distribution(s): 0, 0-30, 0-60, 0-90, 30-90.
- Exit Conditions: *Free-flow*.

Scenario 2:

- Response time distribution(s): 0, 0-30, 0-60, 0-90, 30-90.
- Exit Conditions: *Fruin, Hankin, Polus and HMSO exit flow rates*.

Scenario 3:

- Response time distribution (s): 0-30.
- Exit Conditions: *Fruin, Hankin, Polus and HMSO exit flow rates*.
- Additional Conditions: *Use of Attractor/Discharge/OBSTACLE nodes*.

Scenario 4:

- Response time distribution (s): 0, 0-30, 0-60, 0-90, 30-90.
- Exit Conditions: *Free flow exit flow rates*.
- Additional Conditions: *Inclement weather simulation*.

**4.52 THE BUILDINGEXODUS PREDICTIONS OF THE SH PAVILION EVACUATION TRIALS.**

In the proceeding sections, results of the buildingEXODUS predictions for the SH Pavilion evacuation trials are presented. All the simulations presented in this section were carried out using a Pentium 133 MHz PC with 32 MB of RAM. Each simulation was completed in less than 10 minutes.

(i) Scenario 1:

In this scenario free flow conditions apply at the exit and so the exit flow rate is not capped. This scenario therefore does not make any attempt at including the effects of the inclement weather reported during the evacuation trial. The predicted evacuation times are therefore expected to be significantly shorter than the measured times. The results for scenario 1 are presented in Table 4-19.

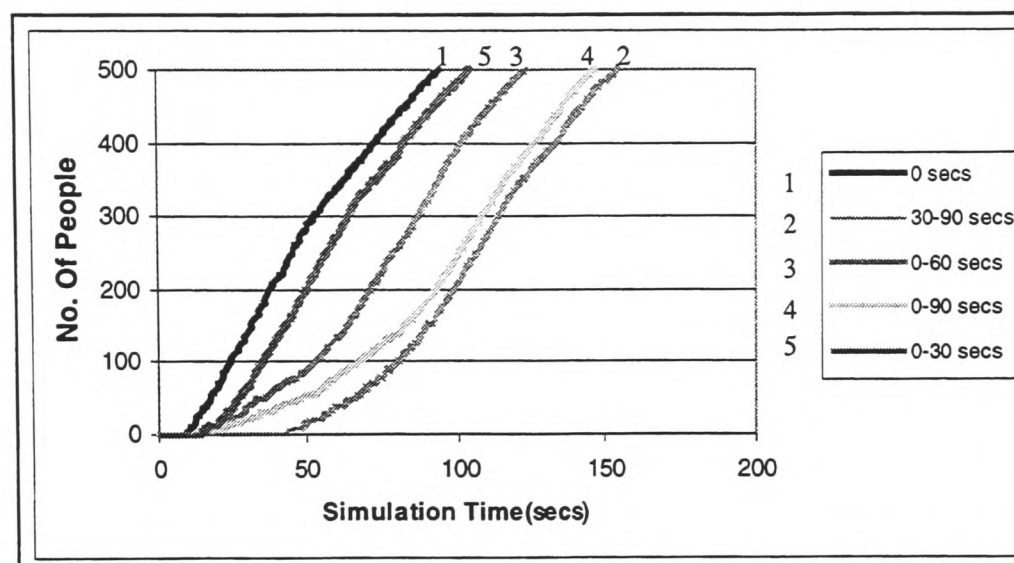
**TABLE 4-19: BUILDINGEXODUS RESULTS FOR SCENARIO 1. RESULTS IN PARENTHESIS INDICATE THE DISTRIBUTION PRODUCED BY THE REPETITION OF THE SIMULATION.**

Flow Rate	Occupant Response Time Distribution				
	0 secs	0-30 secs	0-60 secs	0-90 secs	30-90secs
Free flow.	95 [92-97]	106 [102-108]	123 [121-126]	144 [143-147]	152 [150-154]

As expected, the predicted evacuation times are significantly shorter than the mean measured evacuation time of 158.8 seconds. If the audience is assumed to react immediately to the call to evacuate, a mean evacuation time of 94.8 seconds is produced which is some 40% quicker than the measured evacuation time.



As the response time distribution is increased from zero response to a distribution of 0 – 90 seconds, the mean evacuation time increases to 144.3 seconds, producing an under-prediction of 9%. Note that the inclusion of a response time distribution does not simply off-set the evacuation time derived for zero response by an amount equivalent to the maximum response time. Furthermore, while the 0-90 second response time distribution produces a mean evacuation time only 9% different to that observed, this does not suggest that it more accurately represents the observed evacuation. The extended evacuation time was not produced through attempts to model the impact of the inclement weather conditions and resulting hesitation at the exit.



**FIGURE 4-9: TYPICAL EVACUATION CURVES FOR EACH OF THE RESPONSE TIME CATEGORIES SPECIFIED IN SCENARIO 1.**

A typical evacuation curve for each of the five response time categories is depicted in Figure 4-9. Unfortunately, the time for each occupant to exit the SH pavilion was not recorded during the experiment and so it is not possible to compare Figure 4-9 with actual measurement. However, in the Kose et al simulations [194], a linear evacuation curve was generated which produced a mean flow rate of 5.6 p/sec (see section 4.41). As can be seen from Figure 4-9, the buildingEXODUS evacuation curves are not simply linear, suggesting a variable flow rate was achieved during the simulations. This is further highlighted in Figure 4-10 that depicts the predicted unit flow rate achieved during the evacuation for the instant and 0-90 second response time distributions. As the response time distribution encompasses longer response times, the evacuation curves become less linear (see Figure 4-9) suggesting a more variable flow rate (see Figure 4-10). This is as one would expect since the longer the response time distribution, the greater the phasing of the arrival time of the occupants at the exit. Thus the exit does not have to operate at its peak flow rate for an extended period.

For the zero response time simulations, the mean flow rate is approximately 5.9 p/s. The first occupant exits the geometry in approximately 10 seconds.



In summary, under free flow conditions, buildingEXODUS predicts that the SH pavilion could be evacuated on average within 97.1 seconds if everyone is assumed to move off *instantly*. If the upper limit of the response time distribution is progressively increased up to 90 seconds, the pavilion could be evacuated on average within 147 seconds.

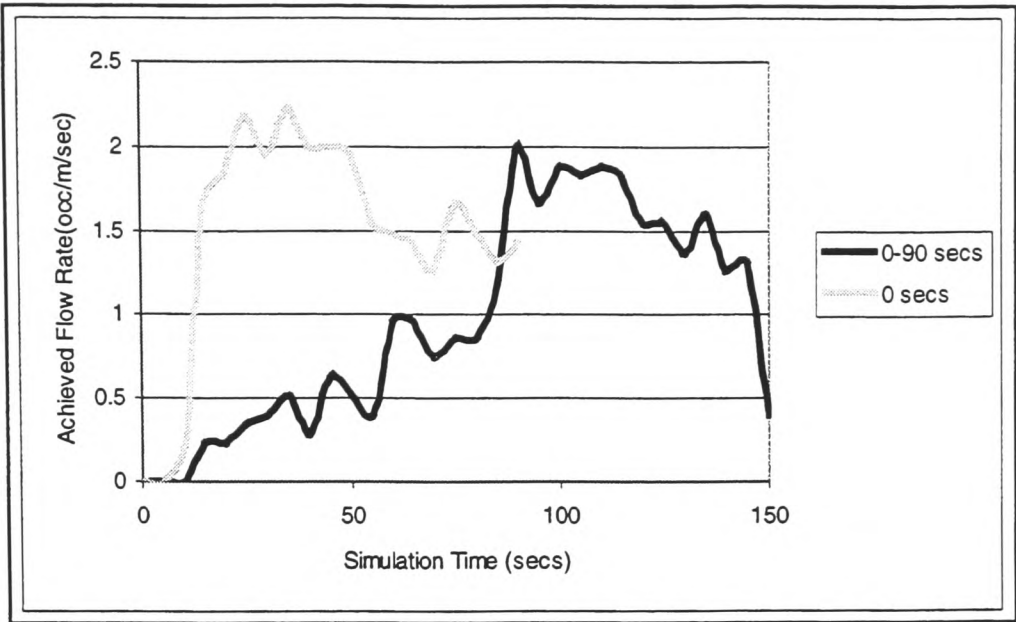


FIGURE 4-10: TYPICAL FLOW RATE CURVES FOR THE INSTANT AND 0-90 SECOND RESPONSE TIME DISTRIBUTIONS IN SCENARIO 1

(ii) Scenario 2:

In this scenario the free flow exit condition used in scenario 1 is replaced with a range of standard imposed maximum flow rates. The simulations are intended to demonstrate the impact of using the prescribed maximum flow rates. As in the previous case, this scenario therefore does not make any attempt at including the effects of the inclement weather reported during the evacuation trial. The predicted evacuation times are therefore expected to be significantly shorter than the measured times. The results for Scenario 2 are presented in Table 4-20.

TABLE 4-20 BUILDINGEXODUS RESULTS FOR SCENARIO 2. RESULTS IN PARENTHESIS INDICATE THE DISTRIBUTION PRODUCED BY THE REPETITION OF THE SIMULATION.

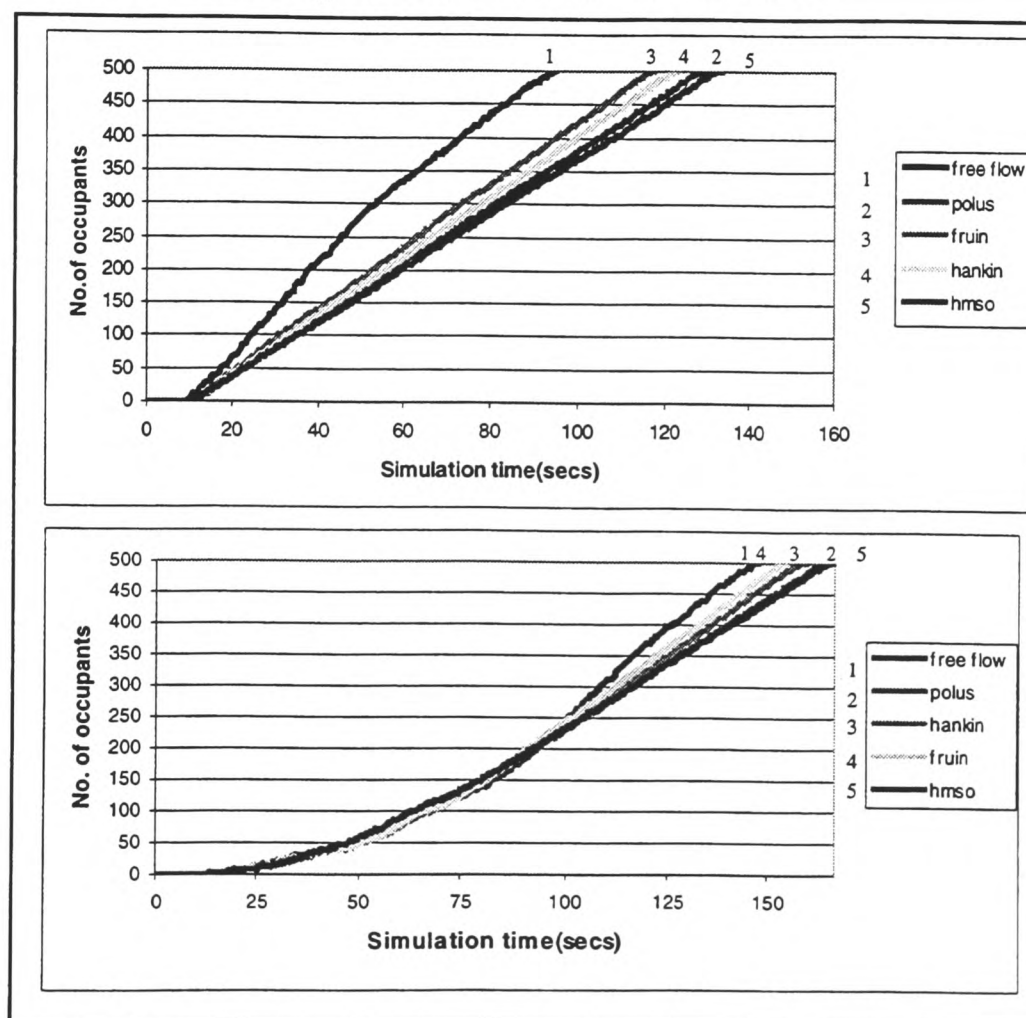
Flow Rates	Occupant Response Time Distribution				
	0 secs	0-30 secs	0-60 secs	0-90 secs	30-90secs
HMSO	133 [130-136]	139 [139-142]	152 [147-153]	166 [160-171]	181 [179-183]
Fruin	114 [113-115]	122 [120-126]	137 [135-139]	148 [146-154]	165 [163-166]
Hankin	124 [122-125]	132 [130-135]	145 [143-147]	157 [153-162]	170 [168-171]
Polus	128 [126-130]	134 [131-138]	150 [147-152]	159 [156-164]	175 [173-177]

We can see a clear increase in the simulation times generated, in comparison to those generated in Scenario 1 (see Table 4-19). These results are expected in the sense that the prescribed flow rates are by their nature conservative. This results in the imposed prescribed flow rates restricting the flow of occupants through the exit and generating longer evacuation times.

A typical evacuation curve for each of the five exit flow rates (including free flow) with zero response time is depicted in Figure 4-11a. Note that the prescribed flow rate curves are strictly linear. This suggests that due to the sudden crush of people at the exit, the exit quickly attained and maintained its maximum flow rate.

As a response time distribution is introduced, the curves become less linear suggesting that the exits are not working to their full capacity for a limited period of time (see Figure 4-11b).

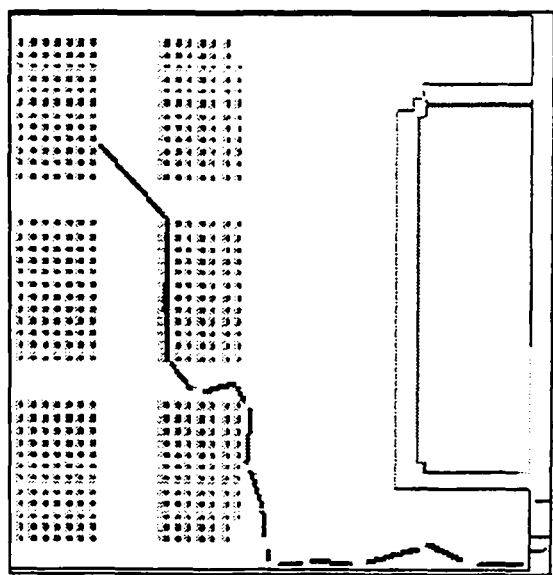
The most severe increase in evacuation times occur with the HMSO [185] flow rate, while the least severe increase occurs with the Fruin flow rates [66]. These results are to be expected as the HMSO flow rates are the most conservative (1.33 p/m/s) while those of Fruin are the least conservative (1.33 to 2.00 p/m/s). The HMSO evacuation times are some 41% greater than the free flow evacuation times with zero response times and 15% greater when a 0-90 second response time distribution is used.



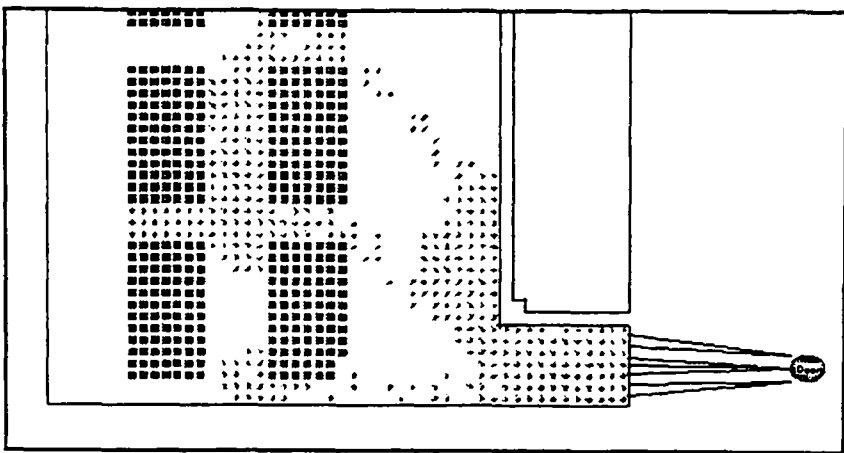
**FIGURE 4-11: TYPICAL EVACUATION CURVES FOR EACH OF THE EXIT FLOW RATE CONDITIONS AS SPECIFIED IN SCENARIOS 1 AND 2 WITH (A) ZERO RESPONSE TIME AND (B) 0-90 SECOND RESPONSE TIME.**

In these simulations, occupants were noted to move along the aisles formed by the rows of seats. A path of such an occupant is highlighted in Figure 4-12. Furthermore, severe congestion was observed during all of the above simulations. This congestion built up from the exit and fed back into the concourse (see Figure 4-13). This congestion

significantly effected the egress of the occupants. These qualitative findings correlate remarkably well with the original observations of the actual behaviour.



**FIGURE 4-12: PREDICTED EGRESS PATH OF AN OCCUPANT IS DEPICTED WINDING THEIR WAY BETWEEN THE SEAT ROWS AND THROUGH THE CONGESTED APPROACH TO THE EXIT.**



**FIGURE 4-13: PREDICTED CONGESTION AROUND THE APPROACH TO THE EXIT. THE SCENE IS FROM THE SCENARIO 2 SIMULATION WITH HMSO FLOW RATES AND 0-30 SECOND RESPONSE TIME DISTRIBUTION.**

**TABLE 4-21: MEAN CWT (SECS) FOR SAMPLE SIMULATIONS IN EACH OF THE SIMULATION CATEGORIES FOUND IN SCENARIOS 1 AND 2. RESULTS IN PARENTHESIS INDICATE THE RANGE OF CWT FOUND IN THE POPULATION.**

Flow Rates	Occupant Response Time Distribution				
	0 secs	0-30 secs	0-60 secs	0-90 secs	30-90secs
HMSO	45 [0-106]	39 [0-110]	36 [0-115]	33 [0-133]	34 [0-118]
Fruin	38 [0-90]	31 [0-87]	33 [0-109]	31 [0-123]	30 [0-105]
Hankin	41 [0-96]	34 [0-96]	34 [0-109]	32 [0-123]	34 [0-118]
Polus	43 [0-104]	37 [0-107]	34 [0-109]	34 [0-123]	33 [0-108]
Free Flow	27 [0-72]	25 [0-78]	26 [0-96]	31 [0-114]	25 [0-97]

A useful engineering parameter produced by buildingEXODUS is the cumulative wait time (CWT) for an occupant. The wait time is a measure of the time the occupant remains stationary after he has started to move. The CWT is the sum of all the individual wait times incurred by the occupant. Thus, the CWT provides a measure of the total time an occupant wastes in congested areas during the evacuation. Ideally, the CWT should

be zero, suggesting that the occupant had an unhindered path to the exit. Displayed in Table 4-21 is the mean CWT for a typical simulation in each of the categories examined in Scenarios 1 and 2.

The free-flow conditions produce the smallest mean CWT suggesting that under these conditions the minimum congestion occurs. Conversely, the largest mean CWT occurs under the HMSO prescribed flow conditions. This suggests that the maximum congestion occurs under these conditions. From Table 4-20 we note that using the HMSO flow rates with zero response time, the mean CWT is 45 seconds. However, throughout the population, the CWT varies from 0 seconds to 106 seconds. From Table 4-19 the maximum evacuation time for this scenario is 136 seconds. This suggests that at least one occupant may have spent as much as 78% of their evacuation time unable to move due to congestion. It should however be noted that less than 6% of the population in this scenario had a CWT greater than 90 seconds.

Differences in CWT results between the various simulations suggest that these simulations differ not simply in the total evacuation time but in the nature of the resulting flow dynamics. This is further demonstrated in Figure 4-14 that depicts the CWT for each occupant in each of the five flow rate categories for response time distributions 0-30 and 0-90 seconds. The trends that emerge suggest that the more restrictive flow rates produce occupants with higher CWT. Furthermore, the response time distribution influences the dispersion of the CWT distribution. With a 0-90 seconds response time distribution, more extreme cases are recorded in the CWT distribution than in the 0-30 second distribution. This is due to two different effects. Firstly, the increase in the range of response times allows some occupants to evacuate with very little interaction with other occupants, decreasing their CWT. Secondly, some occupants, with long response times may be situated in a position preventing other occupants from leaving the seating area, thereby increasing their CWT. The combined effect is to produce a wider distribution of CWT's amongst the population.

While Scenario 2 produces evacuation times that are closer to the measured range of evacuation times than those of Scenario 1, this does not necessarily suggest that the models in Scenario 2 are more accurate. The prescribed flow rates used in scenario 2 are not intended to take account of the effects of inclement weather and the delays this may cause in exiting. Indeed, the prescribed flow rates used in these simulations are intended for use under "normal" exiting conditions. A similar apparent improvement in model

predictions could be achieved by introducing longer response times in the free flow scenario. While resulting in an increased evacuation time and therefore closer to the experimental results, this improvement will not have resulted from a better or more precise model. It is essential that the model should account for the prolonged evacuation time in a similar qualitative fashion to the actual event.

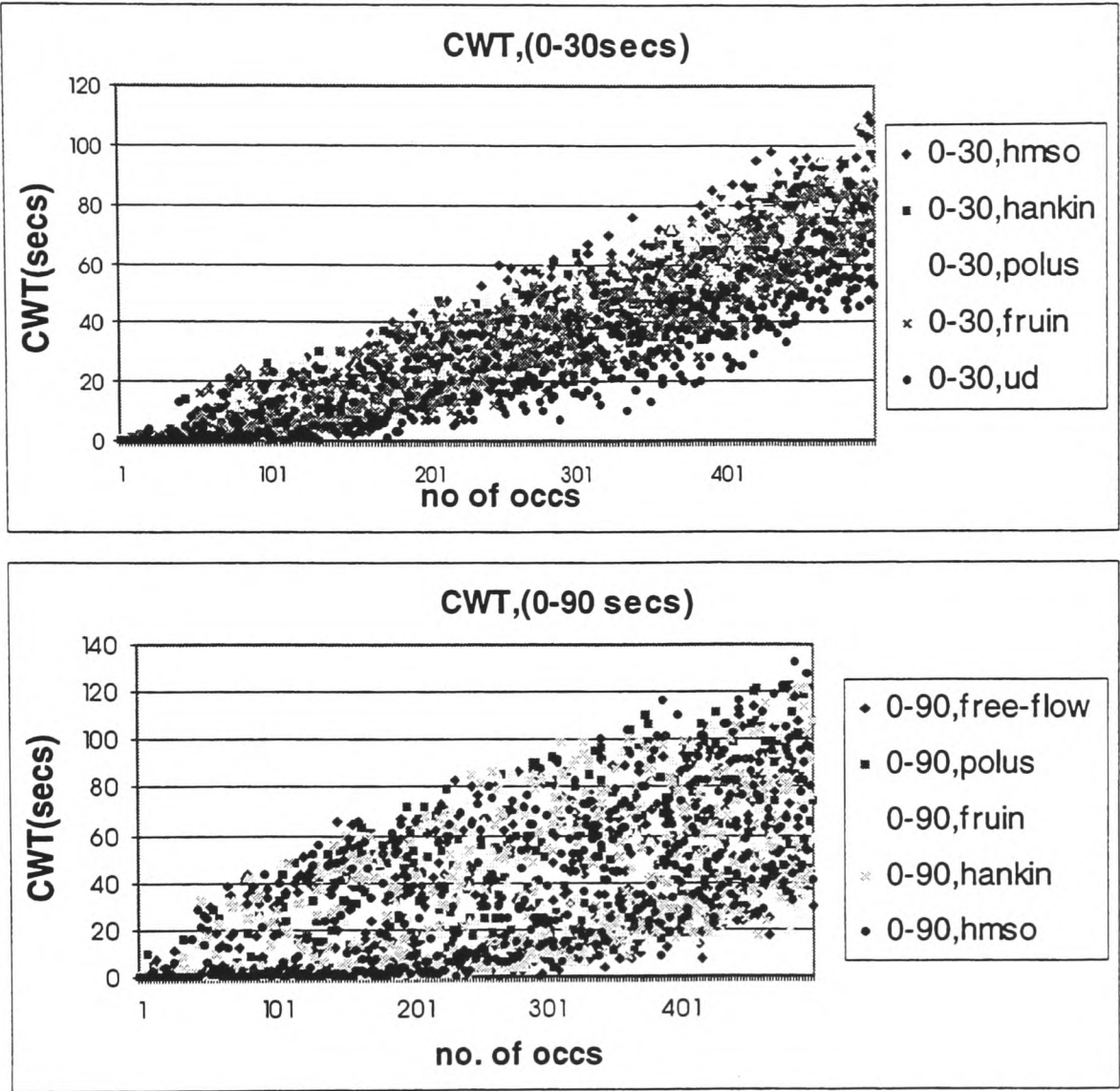


FIGURE 4-14: COMPARISON OF THE OCCUPANT CWT'S FOR THE 0-30 AND 0-90 SECOND RESPONSE TIME DISTRIBUTION SIMULATIONS.

However, Scenario 2 has demonstrated that by decreasing the allowed exit flow rate, similar qualitative behaviour to that observed during the trials can be achieved. By utilising the *USER DEFINED* flow rate option, it should be possible to cap the flow rate at a suitable level to simulate the audience's hesitation in leaving the pavilion due to the inclement weather.

In summary, using prescriptive exit flow conditions, the evacuation time increases compared with that found using free flow conditions. Each of the prescriptive flow conditions produces different evacuation times with the HMSO recommended flow rates producing the longest evacuation times. Under these conditions, buildingEXODUS predicts that the SH pavilion could be evacuated on average within 136 seconds if everyone is assumed to move off instantly. If the response time is progressively



increased to up to 90 seconds, the pavilion could be evacuated on average within 171 seconds.

(iii) Scenario 3:

In this scenario some advanced features of the buildingEXODUS model are used to modify the behaviour of the occupants. The exit conditions consist of each of the five cases examined in scenarios 1 and 2, while the 0-30 second range of response times is used. As in the previous cases, this scenario does not make any attempt at including the effects of the inclement weather reported during the evacuation trial.

Two features will be examined, the use of *OBSTACLE* and *ATTRACTOR/DISCHARGE* nodes. Under non-extreme conditions, occupants have a tendency to maintain a distance between themselves and the confining walls of the enclosure and other obstacles [56,89]. Within buildingEXODUS this is achieved by placing a halo of *OBSTACLE* nodes around the wall or obstacle which is to be avoided. Occupants will avoid *OBSTACLE* nodes if given a choice, and if forced to travel across an obstacle node, the *TRAVEL SPEED* of the occupant is reduced. In scenario 3, *OBSTACLE* nodes are placed along the walls of the pavilion.

A means of removing possible anomalies in the potential map is also examined. This is attempted through the introduction of *ATTRACTOR/DISCHARGE* nodes that locally effect the potential map. *ATTRACTOR/DISCHARGE* nodes are specifically designed to modify the potential map by locally re-seeding the potential. This may be necessary in situations where the potential map does not adequately represent the situation being simulated.

In Scenario 3, *ATTRACTOR/DISCHARGE* nodes are used across the approach corridor to the exit (which is formed by the presence of the stage area). The potential map is seeded such that occupants will be attracted to the centre of the approach corridor. The overall direction of the occupants is still towards the exit, however the preferred route is biased towards the centre of the approach corridor.

To investigate the impact of these modifications, the 0-30 second response time distribution is examined for all of the exit flow rates. These conditions are examined as they produce the highest population densities, whilst not maintaining the unrealistic assumption that occupants react instantly. Results for this simulation are found in Table 4-22.

TABLE 4-22: BUILDINGEXODUS RESULTS FOR SCENARIO 3 (RANGE OF RESULTS GIVEN IN BRACKETS).

Flow Rates	Evacuation Times (secs)
HMSO	141 [139-143]
Fruin	125 [123-126]
Hankin	131 [130-133]
Polus	136 [135-137]
Free Flow.	106 [103-108]

By comparing the results in Table 4-22 with those for Scenarios 1 and 2, we note that there is at most only a 1.2 % difference in the mean evacuation times. Thus, in this case, these relatively sophisticated improvements in the model description result in only minor quantitative changes to the model predictions. This may be expected, as the interaction with the walls is relatively minor. Furthermore, severe congestion develops in the approach to the exit resulting in the filling of this region.

While only producing minor quantitative changes to model predictions, major improvements in the qualitative nature of the simulations were achieved. Figure 4-15 demonstrates the impact of the *ATTRACTOR/DISCHARGE* nodes during the early stages of the simulation. Note the apparent bunching which occurs in front of the stage near the approach to the exit without the use of the *ATTRACTOR/DISCHARGE* nodes.

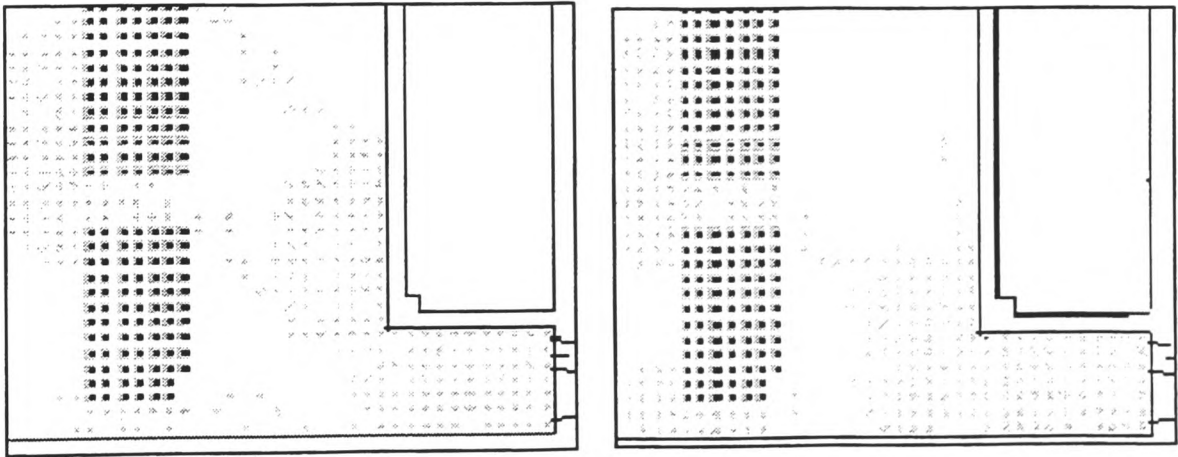


FIGURE 4-15: SCENE FROM THE EARLY PHASES OF A SCENARIO 3 EVACUATION, (A) WITHOUT ATTRACTOR/DISCHARGE NODES, (B) WITH ATTRACTOR/DISCHARGE NODES.

(iv) Scenario 4:

In this simulation an attempt is made to include the effect of the inclement weather conditions on the evacuation.

Due to the poor weather conditions the occupants of pavilion SH were reluctant to venture out into the rain. It is likely that this caused a bottleneck just outside the pavilion

that resulted in congestion in the vicinity of the exit and the subsequent prolonged evacuation time.

In Scenario 2 it was suggested that one way of modelling this effect would be to artificially decrease the allowed maximum flow rate through the exit. Another method involves extending the calculation domain to encompass the region external to the pavilion and continue the simulation in this region. This is necessary, as within buildingEXODUS, occupants are no longer tracked once they have passed through an external exit. At this stage occupants are considered to have left the simulation and no longer exert an influence on the proceedings. By extending the solution domain to the external region of the building and allowing occupants to gather there, it is possible to simulate the external bottleneck and hence generate the resulting congestion. In these simulations the solution domain by the exit is arbitrarily extended by an area measuring 10m x 11m.

If details of the external region had been provided, it would be possible to accurately model this area. As details are not provided a simple court region is added to the geometry which is free of obstacles such as furniture. This region is termed the “reservoir”. The reservoir is not intended to contain the occupants for an indefinite period, its purpose is simply to create a bottleneck outside the pavilion thereby generating internal congestion. It is thus necessary to eventually remove occupants from the reservoir.

Within buildingEXODUS, occupants are removed from the simulation only when they pass through an external exit. Occupants are removed from the reservoir via a device termed a “virtual” exit. This is simply a buildingEXODUS construct with the same properties as an external exit and so acts as an occupant sink. The virtual exit has a definable width and a maximum flow rate or free flow conditions may be prescribed.

Using this approach, the actual exit becomes an internal exit and is simulated using free flow conditions.



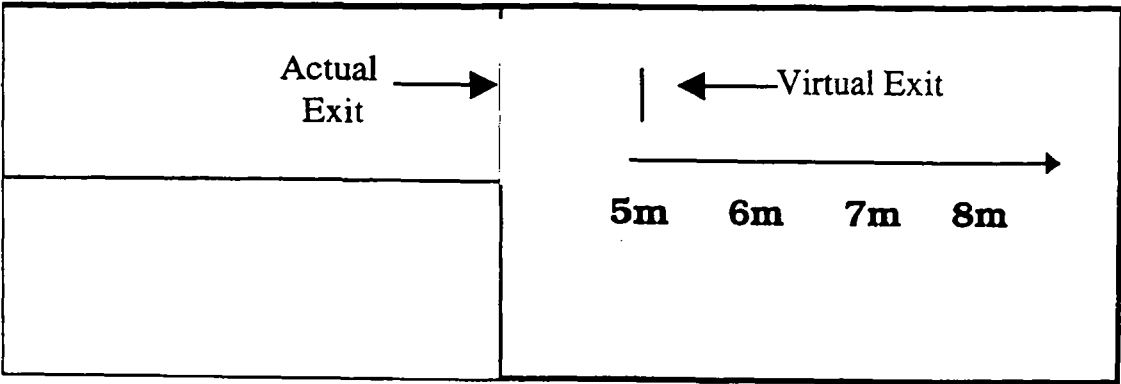


FIGURE 4-16: SCHEMATIC REPRESENTATION OF THE RESERVOIR GEOMETRY AND VIRTUAL EXIT LOCATION.

An arbitrarily restrictive unit flow rate of 1.75 occ/m/sec and exit width of 2m is imposed on the virtual exit. In addition, the virtual exit is arbitrarily located between 6m and 8m from the actual exit (see Figure 4-16). The simulation results are expected to be sensitive to the location and imposed flow rate (i.e. unit flow rate x width) of the virtual exit. These conditions will control the level of congestion achieved in the vicinity of the actual exit.

Finally, the evacuation time for this simulation is determined as the time the last occupant passes through the actual exit, not the time that they pass through the virtual exit. The simulation includes the use of Attractor/Discharge and *OBSTACLE* nodes as in scenario 3. The results for this scenario are presented in Table 4-23.

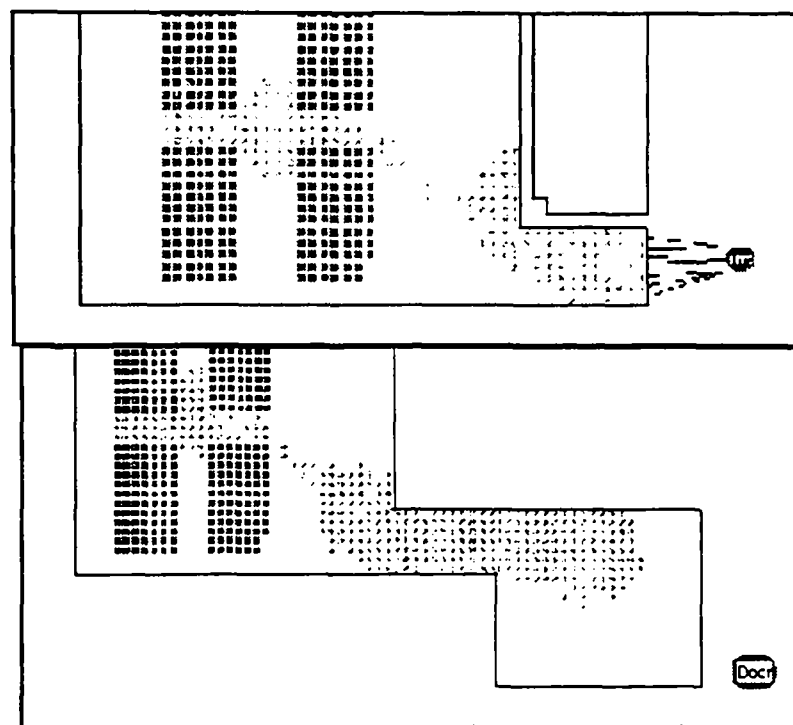
TABLE 4-23: BUILDINGEXODUS RESULTS FOR SCENARIO 4. RESULTS IN PARENTHESIS INDICATE THE DISTRIBUTION PRODUCED BY THE REPETITION OF THE SIMULATION.

Virtual Exit Flow Rate	Occupant Response Time Distribution				
	0 secs	0-30 secs	0-60 secs	0-90 secs	30-90 secs
6m	142 [139-144]	147 [144-151]	154 [150-158]	166 [163-168]	180 [178-182]
7m	133 [130-136]	139 [138-142]	149 [145-154]	161 [157-164]	174 [172-175]
8m	123 [119-126]	132 [130-134]	134 [132-135]	151 [148-154]	165 [163-167]

As noted previously, the overall evacuation time increases as the response time increases. As expected, the results are sensitive to the exact location of the virtual exit. The predicted evacuation times decrease as the virtual exit is moved further away from the actual exit. We now find that the evacuation times have increased compared to those in scenario 1. Under instant response conditions, the congestion that occurs by the exit has increased in all of these cases. When implementing a virtual exit 6m from the actual exit, the mean evacuation time increases from 95 seconds (in scenario 1) to 142 seconds. If the upper limit of the response time distribution is progressively increased up to 90 seconds whilst maintaining the 6m distance, the mean evacuation time increases from 144 seconds (in scenario 1) to 166 seconds.

The effect of the external congestion on the evacuation time decreases as the response time distribution increases. When the response time distribution is small, the occupants arrive at the exit and hence the reservoir virtually at the same time. Thus the reservoir becomes crowded, as the virtual exit cannot remove occupants quickly enough, resulting in congestion within the vicinity of the exit. Figure 4-17(a) depicts the evacuation 60 seconds into the scenario 1 simulation with instant response time. Note the level of crowding in the vicinity of the exit. Figure 4-17(b) depicts the same scene in scenario 4. Note the greater level of crowding and congestion.

As the response time distribution increases, the arrival of the occupants at the reservoir is staggered, allowing the reservoir to empty before huge crowds develop. This in turn reduces the degree of congestion around the exit and results in a correspondingly smaller increase in the overall evacuation time.



**FIGURE 4-17: CROWDING IN THE VICINITY OF THE EXIT DURING THE EARLY STAGES OF THE EVACUATION SHOWING THE IMPACT OF THE RESERVOIR, (A) SCENARIO 1 AND (B) SCENARIO 4.**

Clearly, the inclusion of the reservoir better captures the qualitative behaviour of the occupants as they respond to the effects of the inclement weather. Furthermore, the quantitative results produced during this scenario more closely match the observed results. Assuming a response time distribution of 0-30 seconds and a virtual exit placed 6m from the actual exit, the model predicts that the pavilion can be evacuated in between 144 and 151 seconds with a mean evacuation time of 147 seconds. This compares with observations of 152 to 166 seconds and a mean of 158.8 seconds.

However, it should be recalled that the conditions within the reservoir were arbitrarily set. The nature of the resulting congestion is controlled by the virtual exits proximity to the actual exit and its flow characteristics. Greater congestion and hence delays can be created by reducing the flow characteristics of the virtual exit and positioning it closer to the actual exit.

#### **4.6 CONCLUSION REMARKS TO THE VALIDATION OF THE RELEASE VERSION OF BUILDINGEXODUS**

It is vital that an understanding be developed of the role different forms of validation - i.e. component testing, functional, qualitative and quantitative validation - have to play in the general acceptability of evacuation models.

In this chapter, attempts at qualitative and quantitative model validation of version 2.0 of the buildingEXODUS evacuation model were presented. The data sets used for validation purposes were the Stapelfeldt, Milburn House and Tsukuba evacuation data.

During the course of the validation exercise the data-sets were found to be less than ideal for the purpose of validating complex evacuation models. Information crucial to the success of the validation process was missing in each of the validation cases.

The Stapelfeldt experiments were much simpler in their scope than the other cases and as a result suffered less from omissions of important data. However, due to its simplicity, less insight could be derived from its analysis.

In all of the cases the geometry of the enclosure was not defined completely. In the case of the Stapelfeldt experiment the room dimensions were not completely specified, while in the case of the Milburn House evacuation, details relating to the staircases, possible obstacles and exact exit dimensions were not specified. The Tsukuba data set had a relatively complete description of the geometry, although the exact specifications still had to be derived from a relatively crude diagram.

In all cases the nature of the population was not completely defined. In the case of the Stapelfeldt experiment, this was not too severe a restriction due to the nature of the trials conducted (size of compartment, large population density, expected similarity in disposition of population). However, in the Milburn House evacuation, essential data such as detailed response times, starting locations and exit paths were missing. This problem was overcome through the incremental addition of the information to the cases

examined. The Tsukuba data set also lacked a full description of the occupant population. In addition, the precise nature of the evacuation was not described making it difficult to ascertain the psychological disposition of the occupants. Finally, while several evacuations were observed, only the total evacuation time for each evacuation was reported during the Tsukuba ‘evacuation’.

While the omissions in the Stapelfeldt data still allowed some level of quantitative validation to take place, the omissions from the Milburn house data made any level of quantitative validation highly questionable. However, the data collected from the Milburn House evacuation was useful for qualitative validation purposes, as well as enabling the examination of the model’s sensitivity to the incremental provision of new information. The Tsukuba data-set was particularly useful in its examination of the buildingEXODUS, as it required novel modelling techniques.

In addition to the above limitations, as only a single data point was available for the Stapelfeldt and Milburn House, the *repeatability* of the data is also questionable. This was not a problem in the Tsukuba case, as four data points were available, presenting an increased (although still limited) distribution of comparisons.

It should be emphasised here that these comments refer to problems that arise in the validation of complex evacuation models, i.e. fine node structure with individual person specification. These omissions may have different ramifications for models that use a coarse node structure and treat the population as an ensemble [8]. In general, as evacuation models become more sophisticated, so they will become increasingly sensitive to particular aspects of data sets intended for validation purposes.

On examining the overall performance of the buildingEXODUS model during the Stapelfeldt simulations, excellent agreement between the predictions and the observed evacuation times was found. During these simulations, the sensitivity of buildingEXODUS to both the exit flow rates and the occupant motivation was demonstrated. It should be noted that the buildingEXODUS predictions that agreed most closely with the experimental results utilised free flow conditions at the exit, i.e. a prescribed flow rate was not imposed, allowing the model to calculate the effects of congestion around the exit. When standard flow rates were imposed on the buildingEXODUS simulations, these were found to greatly *over* predict the evacuation times. This is in line with the conservative nature of the “recommended” flow rates.

These results were attained utilising sensible assumptions concerning omissions in the data set, rather than attempts at engineering the outcome. Although only a single experimental result was obtained for each scenario examined, a range of model predictions was generated, with the experimental result falling within the range generated by the model.

The inappropriateness of the Milburn House evacuation for quantitative validation purposes has been examined in depth. However, the limited data set did provide an opportunity to demonstrate the sensitivity of buildingEXODUS parameters, as well as performing some qualitative validation. The Milburn House simulations demonstrated the importance of occupant response times. As noted by Sime [4], response time effects may dominate other factors such as occupant travel rates and travel distances, i.e. the time taken in reacting to the incident may be more important than the travel time. Despite the incompleteness of the Milburn house data set, it was possible to demonstrate the sensitivity of the evacuation times as predicted by buildingEXODUS to occupant response times.

An important qualitative feature predicted by buildingEXODUS was the development of congestion at a particular exit, which was reported during the original report [193]. It was also possible to qualitatively demonstrate the effect of making the “fire” stair unavailable at a predefined time.

Initially, during the Tsukuba validation, the external conditions evident during the original incident were ignored. Under these conditions, the simulations produced evacuation times that were significantly shorter than those observed. The predicted evacuation times were sensitive to the population response time distribution and to the nature of the flow conditions imposed on the exit.

The effects of the inclement weather could be artificially introduced into the simulation by imposing an arbitrarily small flow rate on the exit. However, a superior method was demonstrated; namely to extend the flow domain to the exterior of the geometry thus recreating the exterior crowding and generating the interior congestion. This the preferred method as it better captured the qualitative behaviour of the occupants as they responded to the effects of the external bottleneck and the resulting internal congestion caused by the inclement weather. Using this approach, the model predictions were found to closely match the quantitative experimental results. In addition, buildingEXODUS

was able to reproduce certain qualitative observations such as the tendency for occupants to move through the seating. Therefore the artificial imposition of occupant delays around the exit produced more accurate results than might otherwise have been the case.

As part of the Stapelfeldt, Tsukuba and Milburn House validation exercise, the sensitivity of the buildingEXODUS predictions to a range of variables was examined. These include the occupant drive, occupant location, exit flow capacity, exit size, occupant response times, geometry definition and inclement weather conditions. The buildingEXODUS simulations were seen to be sensitive to all these variables. However, it should be emphasised that the level of model sensitivity is dependent on the nature of the scenarios being investigated.

The buildingEXODUS model has been shown to produce results that were consistent with the relative scenarios. The changing conditions under which the simulations were conducted influenced the outcome, without producing anomalous or conflicting results. However, except for the Stapelfeldt case where the experiment was intentionally designed for simplicity, the results produced were not *qualitatively* adequate. Although quantitatively accurate, the results lacked a behavioural sophistication that would have been evident during the actual crowd movement. In conjunction with the analysis conducted during Chapter 2 and Chapter 3, these inadequacies suggest developments that are required within the buildingEXODUS model.

Problems exist in simulating the usage patterns of the enclosure exhibited during the original Milburn House evacuation. The exact exit usage was only replicated once the user was able to identify the actual occupant usage. This information might not normally be available, especially if the engineer was attempting to predictive the outcome of an evacuation *blindly*. This suggests a means of representation that is not simply based around catchment areas, but is in some way related to the experiences of the occupant is required. As identified in Chapter 2, occupant familiarity is an important factor in the subsequent occupant behaviour, requiring a localised and sophisticated means of representation. This representation was seen to be largely absent from the evacuation models currently available (see Chapter 3).

After analysing the original questionnaires concerning those involved in the Milburn House evacuation, it became apparent that a number of the occupants relayed and received information concerning the existence of the evacuation and the potential

availability of exits. Communication, even in simulated or trial conditions has an influence upon the outcome of the evacuation. Even if occupants were not involved in communication, redirection was evident due to the unavailability of the 'orange' stairwell simulating the incident. This suggests that occupants do not blindly maintain their egress route irrespective of the information available to them. Instead, information is used to shape and adapt their path according to time and safety calculations. In a number of real evacuations (Beverly Hills Supper Club, King's Cross, see Chapter 2) the transferral of information between evacuees enabled a wider scope of behaviour as well as providing early information concerning the existence of a life-threatening incident,. The capacity to represent this behaviour was noticeably lacking in the evacuation models that are currently available (see Chapter 3).

During the Tsukuba movement, the crowd responded to an instruction given to them by a member of staff (a conductor [194]). This information was treated as being of some importance because it was delivered by someone assumed to be privy to specialist information (again as in Beverly Hills Supper Club [52] and in the King's Cross incident [97]). This suggests that a method to represent the identity of those involved in the evacuation is required, as it will impact upon the communication process. More importantly than the precise identity of those involved, the role and position within the existing social hierarchies will be an important factor upon the transferral of information and the behaviour of the occupants. Again, in the vast majority of models currently available this capability was lacking.

The Tsukuba Pavilion scenario produced a number of problems relating to the qualitative aspects of occupant behaviour. Firstly, the occupant movement that was observed in the present model was largely insensitive to the structure. Therefore irrespective of the availability of space, the occupants adhered to the potential map, even if this meant staying in close proximity to the enclosure boundary (this behaviour was also evident in the other validation cases, but was less noticeable). The proximity of an occupant to other members of the population was also not considered in the occupant's movement, producing unusual and inappropriate occupant formations. This was particularly evident in the corridor leading to the exit in the Tsukuba Pavilion where the engineer was required to manipulate the geometry so as to ensure more realistic occupant movement. To overcome this problem, the occupant's path should not be entirely based around geometric considerations, but should also relate to the preferences

of the individuals involved. This might include maintaining a distance from the enclosure boundary or from other occupants.

Fundamental to the Tsukuba Pavilion movement was the fact that prior to their exit, a number of occupants *delayed* their movement due to the weather conditions, causing extensive blockages. In the present model, this was represented by either imposing flow rate restrictions upon the external exit, or manipulating the physical space. A more satisfactory means by which to replicate this effect would be to have the conditions represented more accurately rather than manipulating existing and possibly inappropriate mechanisms; namely to have the occupants halting at the precise position that they did originally. This might not only be used to represent the actions of the evacuees during the Tsukuba movement, but might represent a number of the actions such as viewing signage, a difficult terrain, etc (see Chapter 2). The perception by the occupant of the potential hazard posed by the incident will be affected by this information, as it will be by the local environmental conditions and their previous experiences. This interpretation of the seriousness of the situation and the manner in which this perception alters significantly influences the decision-making process (see Chapter 2). For instance the occupants delaying the movement from the Tsukuba Pavilion because of the inclement weather conditions may have been more willing to evacuate if the enclosure was on fire. This identifies the necessity for a more dynamic representation of occupant motivation.

An important consideration highlighted by this work is that any validation exercise must be scrutinised to identify both the results generated and the considerations and assumptions on which they are based. Of great importance are the assumptions usually associated with the nature of the experimental data used for the validation.

These simple validation cases have suggested a number of behavioural inadequacies in the present model. These suggestions, coupled with those provided by the behavioural analysis in Chapter 2 (culminating in the development of the proposed model encapsulated by Figure 19) and the model expectations of Chapter 3, now provide the basis for the proposed improvement and development of the buildingEXODUS behavioural model. These developments are outlined in some detail in Chapters 5-8.